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CRITERIA FOR VALUE ENGINEERING

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FOREWORD

This report was prepared by the Radio Corporation of America of Camden, New Jersey, for the Rome Air Development Center, Reliability Branch, Engineering Division, Air Force Systems Command, United States Air Force, Griffiss Air Force Base, Rome, New York. Mr. Russell E. Purvis was the project engineer and principal investigator and Mr. Harvey R. Barton the project manager. Other RCA project personnel were R. L. McLaughlin, J. T. Glass, and I. H. Young. Mr. Julius Widrewitz was U.S.A.F. project monitor. Other U.S.A.F. project personnel were E. Simshauser and J. Klion. This study was made under Contract No. AF30(602)-3850, and was conducted during the period July 1, 1965 - June 31, 1966. Project Nr. is 5519, Task Nr 551901.

It should be recognized that the definition of "Value" used herein differs from that currently accepted in the industrial Value Engineering fraternity. "Value", as used here, describes the imputed worth, as of a system for accomplishing its objective, where the basis of worth is the worth of the objective.

The reason for the departure from the definition in current use in the Value Engineering field is twofold. First, it is desired to encourage Value Engineering effort on the part of those individuals not presently so employed. Second, and more important, the value function was required to be useful in optimization operations. As described in the report, the dimensional compatibility required for optimization favors the separation of performance and cost factors. The proposed value function permits optimization of performance with maximum cost constrained for optimization of cost factors with constrained minimum acceptable performance. The second type of optimization is the more frequent requirement of value engineering. In addition, the proposed definition permits comparison of systems designed for different functions, which is essential for evaluating systems of overlapping capabilities, or alternate mixes of systems for accomplishing a complex function.

Frequently, it is inconvenient (or undesirable from the standpoint of national security) to use objective worth as an operating numeric. In comparison of alternatives with the same function, this is unimportant, since objective worth is invariant, and only the performance aspect of "value" differs between the alternatives. Fortunately, though, where it is required to determine "Value" for systems having different functions, the cost paid for an acquired system to accomplish the function can

be utilized as a lower bound on its "Value."

If it is desired, mental conversion can be made from the definitions of this report to those currently used by the Value Engineer, by considering "Value" defined herein, as worth, and "Value" divided by cost, as value.

This document is not releasable to CFSTI because it contains information embargoed from release to Sino-Soviet Bloc Countries by AFR 400-10, "Strategic Trade Control Program."

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange or stimulation of ideas.

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ABSTRACT

This report presents a value analysis methodology designed to widen the scope and improve the effectiveness of existing conventional techniques of value analysis, by reorienting the emphasis towards the conceptual phase of development. At present, the methods and techniques of value engineering, as generally recognized and contractually practiced, consist of re-evaluation of functions and incentive reward for any pertinent reduction in cost of acquisition. Basically, the report describes a development of the concept of value and its quantification, along with prescribed methodology for systematic analysis, permitting value optimization with respect to total expected resource cost.

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The major objectives of study contract AF30(602)-3850 were to investigate the theoretical feasibility and practical advantages of developing an engineering (synthesizing) procedure for achieving high levels of value, exercising positive control, promoting value assurance, and accomplishing cost avoidance during the definition, design and development, and operational stages of a product's life cycle.

A value engineering methodology was developed compatible with configuration and performance engineering relating value, function, performance, and total resource costs. The value engineering procedure employs a mathematical modeling technique in the form of a cost difference equation, which permits the evaluation of design-support alternatives and identification and selection of the least-cost alternative from among those originally considered. The mathematical model operates on quantitative, reliability, maintainability, operational readiness, and acquisition and support cost factor inputs. Hence, by selection of the least-cost alternative, a margin of assurance is provided that performance parameter requirements, as well as function and total cost, have been evaluated.

A field test and statistical validation of the technique were contemplated. However, these were not possible for two reasons. A least-cost alternative is selected on a comparative basis and only with respect to those alternatives originally considered. Consequently, in the program definition and early design stages of development where no historical/theoretical value standards exist, it cannot be positively stated or demonstrated that the alternative chosen represents an optimized state. Secondly, the "factual cost" information necessary to facilitate a real-cost versus a project-cost comparison was not available in the detail required. Consequently, the comparison of two sets of projected-cost figures would prove little. To provide some measure of confidence in the accuracy of mathematical modeling results, a procedure for detecting and adjusting error in least-cost alternative selection was furnished.

The results of this study should not be construed as being conclusive, nor the techniques developed understood to be the panacea. This research effort represents the formulation of just one approach and one step toward satisfying a growing need for a value concept and procedure compatible with other system engineering practices.

As future work, it would be desirable to perform an additional number of model applications to actual case studies to establish technique integrity and investigate the advantages of computerizing the iterative procedures to simplify the mechanics of application and minimize calculation error.

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CRITERIA FOR VALUE ENGINEERING

1. INTRODUCTION

1.1 General

Value engineering had its birth in the commercial world, where it has continued to be aggressively and beneficially applied. Value engineering has also come a long way in military applications, where it transcends the existing commercial application domain. The emphasis in military applications, although first assuming the perspective of commercial application, has consistently continued to be pushed to the detail design and system design phases of system development. This report attempts to conceptualize value engineering analysis as a systematic quantitative technique embodying a formal mathematical structure which permits optimization of value.

The dependent variable in the technique structure is total expected cost of acquisition, operation, and support, as measured in recurring and non-recurring cost over the lifetime of an item or system.

The time phasing of the application is from pre-award phases of system development to design freeze.

In this report, value engineering is viewed as a field of engineering directed to development of systems having appropriate or specified values in the accomplishment of their missions, at least cost; value analysis is considered to be the systematic application of analytical techniques used to assess the value and cost of a system or portion of a system.

There is no attempt in this report to travel the already well-trodden paths in value engineering, nor is there a deliberate attempt to enhance the engineer's thinking or idea generation abilities, except perhaps by providing an analytical foundation and framework for a standardized approach to the projection of cost ramifications of particular decisions.

Within the limitation of this program, idea generation should be assured through capitalizing on competitive aspects of defense spending, thus letting necessity mother invention.

One of the major problems remaining in systems and equipment development is the lack of knowledge on the designer's part of how to

project his design into its operation and support environment. This inability is believed to derive from two sources: first, lack of basic knowledge about the support system, and second, lack of definition of the intended operation of the system or equipment.

The required cost analysis associated with the contractor must be, within his responsibility, consistent with contractual relationships; whatever tradeoffs are performed, and generally, many are required, are best left to contractor expertise. A procedure for cost accounting and control, directing tradeoffs, and providing competitive incentive is developed as an integral part of the value analysis methodology. This technique, for contractors not already employing something similar, should significantly enhance a contractor's capability for cost competitiveness and delivery of a technically suitable product.

A note of precaution is appropriate; it is impossible to predict with certainty the behavior of an equipment in a future environment that is not completely defined, particularly if the equipment exists only on the drawing board. Nevertheless, an attempt must be made to maximize the probability of selecting the best design-support candidate from several alternatives that satisfy the user's operational requirements.

The advantages of the proposed technique are that it is relatively simple to apply, it ensures that all significant costs are considered, it imposes a standardized discipline, and since it compares all alternatives on the same logistic basis, the predicted least cost solution has the highest probability of becoming the actual least cost solution.

The basic principle of value analysis expressed in this report is:

> Value decisions at all levels of hardware development are made with reference to the total cost and value implications of the end product, including operation and support.

The value analysis technique is predicated upon the end product in its intended environment over its expected lifetime. This is the essential starting point of this presentation.

1.2 Background

1.2.1 Present Status - The evaluation of function is the present state-of-the-art of value engineering theory. The basic tool may be summarized as a series of questions directed to function evaluation:

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a. What is the product?

b. What is the designed function of the product?

c. How well does the product perform the function?

d. Are there acceptable alternatives for the design of the product for cost reduction and comparable quality?

This value engineering approach represents a qualitative, rather than a quantitative process.

This tool, applied to military value analysis, takes the following additional forms:

a. Question constraints of contract. Does the contract cover or exceed the requirement of the function of the product? There are two types of requirements generally invoked in contracts, system operational requirements and military specification standards. System operational requirements constitute the big picture, and are generally peculiar to the system. These requirements are mission environment oriented. Military specification standards are detail part performance requirements.

b. Question the mission of the product. Will the product properly perform the mission called for in the contract and specifications?

c. Question constraints of the "abilities," e.g., reliability. Are the constraints of the other "abilities" compatible with the requirements of value for cost reduction?

d. Question alternatives to the design. What alternative designs are possible to perform the required function of the product within the parameters of specifications, cost, and value?

e. Question the parameters of the function of the product. Will the product perform the required function with the present design?

The existing value methodology is recognized primarily as an after-the-fact cost reduction mechanism. In reality, considerable value analysis effort is performed in the proposal, definition, and design phases of system development; but it is given scant recognition as such, due simply to the mensuration problems associated with cost savings.

There is in value literature a wealth of ideas on generation of alternative devices, both of a general nature and as categorized by problem type, e.g., to buy or make (See Appendix I for useful notes on selective application of value analysis).

1.2.2 Present Problems - The existing problems of the value engineering discipline are as follows:

a. Need for a quantitative criterion for value, pointing up the difference between value and cost.

b. Need to orient value analysis to total expected resource cost.

c. Need for a feasible systematic procedure for evaluation of feasible alternatives.

d. Need to reorient value analysis to the objective of elimination of excessive cost, rather than reduction in cost, or do it right the first time; e.g., how much can be saved by decreasing the value of the system (decreasing performance goals, viz., reliability)?

e. Need to project alternatives into total cost picture early in the conceptual phases of system development, thus providing a means of making the systems, circuit, and packaging engineers aware of total cost implications.

1.3 Value Engineering Technique Requirements

1.3.1 General - A general value engineering methodology must meet certain specific requirements, such as:

a. The desired method should be useful for objectively quantifying value, as follows:

   (1) As a tool for design decision through all project phases.

   (2) In the development of proposals.

   (3) In the evaluation of proposals.

   (4) For monitoring the value level of systems/equipment undergoing development.

b. The method should have application to most military systems, equipments, missions, and situations.

c. The method must be technically valid and useful in practice for these reasons:

(1) It must provide realistic guidance for trade-offs between functional levels of performance and the costs of ownership and operation.

(2) It should take into account the skill level of the average user (both contractor and customer), and the conditions under which it will be used.

(3) The data required and the actions to be taken to reach meaningful decisions must be sequenced and timed to match normal program phasing.

(4) The method should be capable of adjustment to maintain its validity in the face of advances in design, systems support policies, and mission requirements, as well as advances in analytical tools and the quality of available data.

(5) The degree of refinement of a model or technique should be compatible with the basic accuracy and variability of the data needed for its use, and the sensitivity of the output to variations in in-put.

(6) The time and cost required to carry out the procedure at any phase of the development cycle should be compatible with design schedules and budgets. The cost of carrying out the procedure must not be disproportionate to the gains expected from its use.

In order to assure meeting the needs outlined in 1.2.2. and requirements (a), (b), and (c) of this section, it is essential that the technique be structured upon a definition for value which can withstand a logical analysis. Accordingly, the characteristics of value are first examined, which are necessary to meet requirements of a useful Value Engineering technique. In the past, a number of factors have militated against meeting these requirements, and care has been exercised in developing the approach so that the same pitfalls can be avoided.

One danger is the failure to recognize that value has an existence independent of cost. The value of a system measures its quality of usefulness, not the cost of ownership. For instance, a technological breakthrough can drastically reduce the cost of

equipment without affecting the value of the equipment at all; or equipment reliability can be significantly improved without a cost increase, but with an <u>evident</u> increase in value through increased probability of achieving the mission. A system may be developed which can replace two existing systems, and with equal satisfaction. Its value is equal to that of the two existing systems, <u>regardless</u> of whether it costs more or less than the two.

A second problem is the not uncommon belief that all value parameters can be optimized at once. In most real cases (given a sound design to start with), it is not feasible to improve one function, indiscriminately, without affecting others.

A third pitfall is a widely held tendency to look for absolute invariant value independent of the particular application and the particular user. The value of a glass of water is quite different to a man on the desert and to a man drowning in a lake. Obviously, an element of value is desire or need.

A fourth hazard stems from overlooking the relationship between the value of a system and the worth of its mission or objective. For instance, a battleship cut up for scrap has far less value than when it proudly joined the fleet, yet many more dollars have gone into the operational and scrapping costs. Certainly, scrap is a less worthy objective than the ship's design mission. It is also true that a perfect mousetrap does not have the value of a fine home, as evidenced by the fact that the customer will not pay so much for the mousetrap.

It is desirable not only to develop criteria for measuring value, but also to develop criteria for selection of areas of high yield. This will involve elements of timeliness and feasibility, as well as such elements of yield as annual or contract cost of producing, the cost of operation and maintenance, complexity, ration of special parts to standard parts, state-of-the-art, design maturity, and remaining useful life.

2. VALUE CONCEPTS

2.1 General The basic technique of value engineering/analysis proposed in this report hopefully provides an improved tool of great potential benfit to a wide range of likely users, Governmental departments, especially the military, as well as private industry. The prescribed methodology is designed to achieve a specified objective at a minimum investment of resource cost over the life cycle of the system, a goal of acknowledged interest to the DOD and the USAF; that is, achievement of specified functions at minimum total expected resource costs over the life of the system.

The following views on the changing concept of value engineering were expressed by Mr. George E. Fouch, Deputy Assistant Secretary, DOD, in a speech entitled "A New Look at Value Engineering in the Department of Defense"*:

"To be truly effective, value engineering must be an integral part of the mainstream of the total management process. Only in this way can value engineering properly contribute to our goal of achieving improved weapon systems at minimum total cost of effective ownership and use for their planned life cycle. Value engineering actually is, as we know, a purposeful, orderly methodology for increasing the return on investment on specific targets of opportunity with no loss in required performance. I am using the term return on investment in its broadest context. To the military, this could mean many things. It might mean, for example, lower acquisition cost, but it might also mean lower total cost by decreasing logistic and operational cost, although increasing acquisition cost. An imaginative value engineering program, for example, has the effect of implementing quality and reliability objectives by simplifying design and focusing testing and inspection on essentials, or it might mean more defense capability for the same amount of dollars. For make no mistake, VE is a tool capable of making desired military capabilities economically feasible, as well as a tool for cost reduction. To industry, by return on investment, I mean increased profits or improved competitive position. VE adds a new financial dimension to the entrepreneurial aspect of defense contracting.

In this light, VE differs from long established techniques and methods in that these have emphasized a single functional

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*Presented at the Value Engineering Symposium, sponsored by the Society of American Value Engineers, May 24, 1966.

management orientation, whereas VE crosses all functional lines in the interest of more efficient achievement of a higher level management and objective. This is a broad dimension, but one which is within the definitions and policy for VE in the Department of Defense today".

The important differences between the orientation of the technique presented in this report and conventional value analysis lie in the areas of application. The proposed technique is to be applied in the conceptual, definition, and design phases, whereas conventional value engineering is generally directed to minimizing acquisition costs, and usually exercised under contractual incentive types of contract. This latter approach is quite legitimate because of the impossibility of evaluating consistently the savings through value engineering efforts at earlier conceptual and definition phases, nor should they be required to be demonstrated. The position taken on this point in this report is that the aim is to eliminate alternatives requiring unnecessary costs before these costs are incurred. Measured in this way, a product which undergoes significant cost reduction in the acquisition stage is poorly designed, depending upon answers to the following questions:

a. Did a preferable alternative exist at the time the initial design decision was made?

b. Does additional information exist now which did not exist previously?

c. Was the initial design decision made using the best information available?

d. Were the alternatives projected into total life cycle?

e. Were chance events weighed and/or explored?

2.2 Value Fundamentals

2.2.1 General - Value has a generally accepted definition of long standing in terms of lay usage. This section considers definition of the term as it is used and develops from this definition a general value model possessing the logical structure required for solution of complex value engineering problems.

2.2.2 Development - Value is defined as the imputed quality of usefulness for a specific purpose. Imputing in this context

describes derivation of a characteristic in terms of measurable parameters. The definition differs from that of "worth" only in that "worth" generally is used to express an intrinsic quality, whereas "value" expresses an imputed quality. These definitions are explicitly and implicitly compatible with general usage. Logically stated,

$$V(f)=p(f)w(f), \tag{1}$$

where

$V(f)$ = the assigned value of the function (f), measured in imputed resource dollars, and

$p(f)$ = the imputed probability of requiring the function, (desire, or need, discussed in 1.3.1) and

$w(f)$ = the worth, measured in resource dollars, of having accomplished the required function (f).

System value becomes

$$V_f(S) = p_f(S)V(f), \tag{2}$$

where

$V_f(S)$ =the assigned value of the system (S) for accomplishment of the function (f) in imputed resource dollars,

$p_f(S)$ =the probability of accomplishing function (f) with system (S) = effectiveness.

The value of a system for achieving a required function is dependent upon the value of the function, and upon the capability of the system for achieving it. Value, considered here, is independent of the means by which the system implements the achievement, and of the cost of system acquisition and support.

2.2.3 <u>Margin of value</u> - The conventional profit margin related to value of a system is represented simply as

$$\Delta V_f(S)=V_f(S)-C(S), \tag{3}$$

where

$\Delta V_t(S)$ = the margin of value, or the return in resource dollars in excess of the investment, and

$C(S)$ = the resource dollars invested to achieve the expected return $[V_t(S)]$.

2.2.4 Military Value Model - Modern military systems can be generally predicated upon a single type of mathematical model. To illustrate its application, consider the following development of this value concept, applied to a defensive system. An offensive system is evaluated by means of the same model, with appropriate modification to the objective value parameter.

An offender will launch an ICBM against a specific location, with imputed probability (q). Detonation of the warhead on target will cause damage with worth [W(L)]. The probability of succes of the mission is (r).

A defending system is planned with probability of success (effectiveness) (v). Success is defined as the reduction of damage to W(L'). The defense system is considered a deterrent to ICBM launch, reducing its probability from (q) to [p(f)<q].

The value of the system is the expected gain from its acquisition

$$V(S)=qrW(L)-r(1-v)p(f)W(L)-rvp(f)W(L') \qquad (4)$$

$$=rW(L)[q-p(f)\ (1-v)]-rvp(f)W(L').$$

In words, the value of the system equals the damage eliminated if it works (which is equal to the damage accruing, if we do not acquire it), less the damage accruing if our system does not work, and the residual damage if it does work.

If we ignore the deterrent capability of our system,

$$V(S)=rvp(f)[W(L)-W(L')], \qquad (5)$$

that is, the system's value is the product of

a. The probability of requiring its function [p(f)],

b. The probability of accomplishing the function with the system (v), and

c. The assigned value of the function, as measured by damage eliminated, [p(r) [W(L)-W(L')]].

The task of the value engineer is to assure achievement of required system value at least cost.

The problem may be stated:

Minimuze total cost, subject to

$$V_f(S) \geq P_0(S)V(f), \tag{6}$$

where

$V_f(S)$ = system value,

$P_0(S)$ = minimum allowable probability of accomplishing function (f), or minimum effectiveness level, and

$V(f)$ = assigned value of function (f).

The environment of the value engineer includes an objective function which is specified. His control of this function is to ensure at least the minimum value of the effectiveness function, or probability of accomplishing the objective, $[P_0(S)]$, at minimum cost (See appendix II for further discussion of value modeling and technique analysis).

2.2.5 Definition of Objective - Let (E) designate a set of parameters describing the effectiveness of the system under evaluation.

$$E=E(e_1, e_3 \ldots e_n) \tag{7}$$

Let (E_0) designate the set of parameter values (e_{i0}), having the minimum acceptable performance numeric associated with each parameter (greater than which there is no explicit advantage for the system). This set of parameter numerics expresses the relative value (V) of the system, in comparison with an alternative having the same objective.

It should be recognized that the system represented by the minimum acceptable value for each performance parameter (e_{i0}) is not necessarily the least costly system. Indeed, it is frequently possible to find a less costly alternative which provides better performance in one or more performance parameters.

Figure 1 illustrates this relationship, where (e_{i0}) is

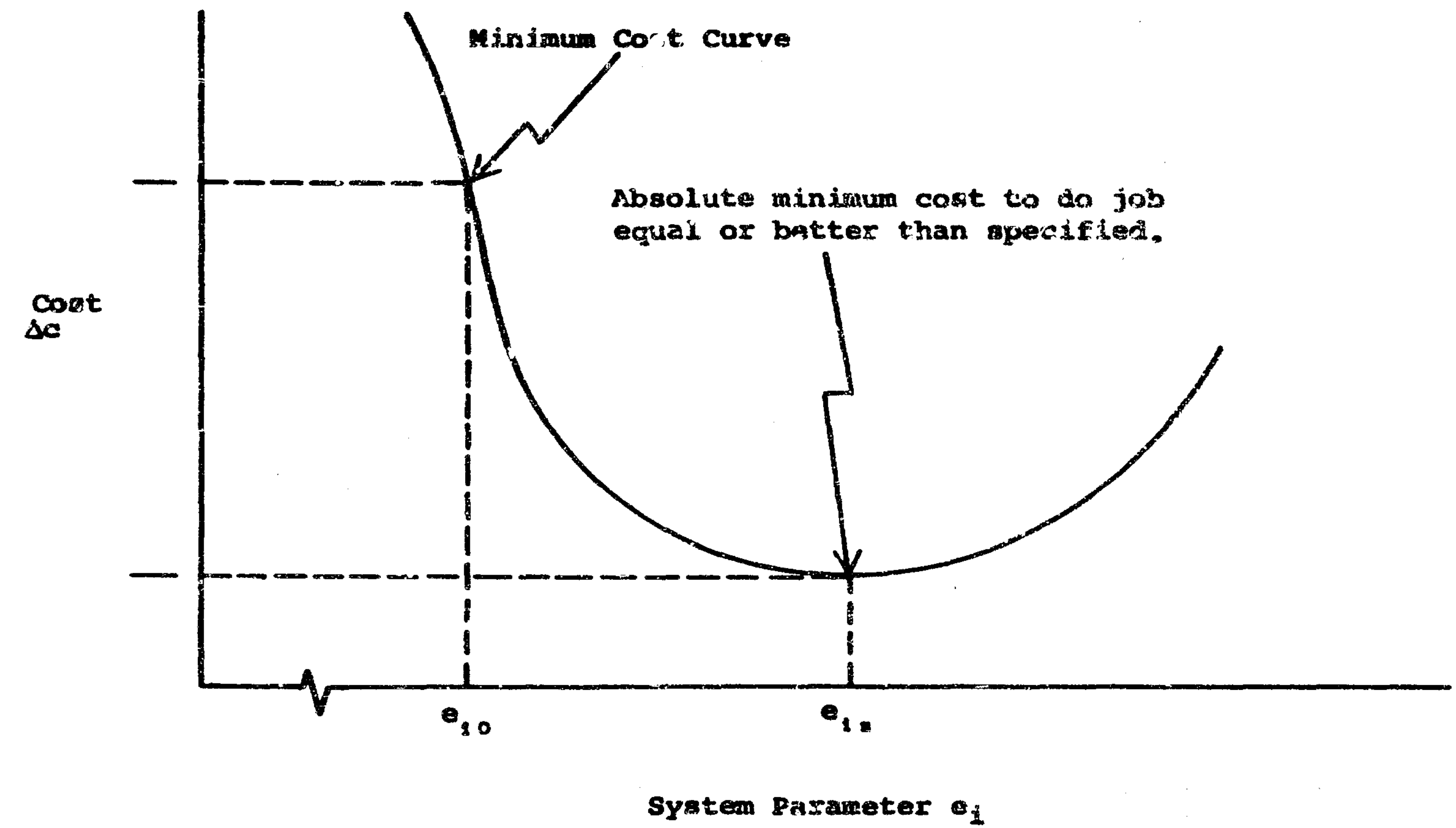

Figure 1. Cost Changes

the specified numeric from the systems study, beyond which further improvement does not contribute significantly to system effectiveness, and (e_{22}) is the absolute minimum cost point).

Most examples of cost reduction result in increased performance, i.e., beyond requirements.* For example, a fringe benefit of cost reduction resulted in an increase in reliability of 30 percent of Class I changes and 48 percent of Class II changes.

This implies misdirection from the existing definition of value, as well as from value analysis. The difficulty arises from the tacit assumption that achievement of a quantitatively specified objective at minimum cost results in the absolute minimum cost.

The value engineering criterion or objective now becomes

$$\text{Objective: Minimize } T=A+S, \quad \text{Subject to } E \geq E_0, \; D \leq D_0, \tag{8}$$

Where A= cost of acquisition,
S= cost of support,
D= delivery lead time, and
D_0= maximum acceptable delivery time.

The model may be expressed also in the form

$$\operatorname{Min} F(T) = S + \lambda_3 (A - A_0 + r_3^2) + \lambda_1 (E - E_0 - r_1^2) + \lambda_2 (D - D_0 + r_2^2), \tag{9}$$

where

$$E - E_0 - r_1^2 = 0 \qquad E \geq E_0$$

$$D - D_0 + r_2^2 = 0 \qquad D \leq D_0$$

$$A - A_0 + r_3^2 = 0 \qquad A \leq A_0,$$

*"Fringe Effects of Value Engineering, DOD", Value Engineering Committee of the American Ordnance Association, Washington, D.C., May, 1964.

where

(λ) is a Lagrange multiplier, introduced to ensure the proper dimensionality along with numerical value, and (r_i) is a slack variable necessary to ensure that the inequalities are satisfied.

3. GENERAL VALUE ENGINEERING/ANALYSIS METHODOLOGY

3.1 Government Reponsibilities

In the presence of a specified objective function, the control of system value is exercised through controlling the system's capability for accomplishing its objective. In order to ensure design value, the system design must be implemented in strict compliance with its objective. Accordingly, a problem definition procedure is followed, whose ultimate objective is to establish value parameters and consequent design constraints. This is the responsibility of the buying agency. The general procedure follows:

a. Develop mission requirements

The system objective is described from such a standpoint and in sufficient detail as to establish capability requirements and a system cost target. An example follows which establishes partial requirements for a system design.

Example:

(1) Target:

(a) Radar image 1 square meter.
(b) Velocity 1 kilometer per second.
(c) Altitude 500 meters.
(d) Evasive action capability - 2 degrees per second^2.
(e) Nuclear warhead.

(2) Intercept Requirements:

(a) Kill distance 20 nautical miles from system base.
(b) Probability of killing a randomly scheduled target, 0.95 at 20 nautical mile radius.

(3) Environment:

(a) Temperatures, -20 degrees Fahrenheit to +160 degrees Fahrenheit in direct sunlight.
(b) Intercept capability not seriously impaired by darkness, fog, electronic jamming (broadband) 50W/kHz).

b. Develop System Performance Parameters

The system configuration is broadly defined, to the degree necessary to describe accomplishment of the mission. This task is normally accomplished by the Government, sometimes as a result of contractor feasibility studies.

Example:

From the previous mission description and a comparison of alternative means of accomplishing it, the decision is reached that the system will include the following:

a. Solid-fuel missile.
b. Radar detection, tracking of target, guidance, and homing of missile interceptor.
c. Nuclear interceptor warhead.

From correlation of system characteristics with the mission requirements and tradeoffs of system characteristics, specifications are established for system performance parameters such as:

a. Radar detection resolution and range.
b. Radar tracking error.
c. Guidance error.
d. Missile velocity and acceleration.
e. Missile maneuvering capability.
f. Missile warhead kill radius.
g. System reliability.
h. System operational readiness.
i. System downtime limitations.

Figures 2(a) and 2(b) indicate applications of design and operational parameters to be furnished the contractor by the Government in the Request for Proposal. At this point in system requirements definition, system and subsystem cost goals are assigned for delivered end items. A Request for Proposal is developed, incorporating the end item cost goals to provide a system which at least meets the minimum set of performance parameters, which corresponds to the value of the effectiveness function.

In addition to cost goals and minimum performance parameters, the Government assigns requirements for adherence to certain general specifications describing methods of producing,

VALUE PARAMETER APPLICABILITY

System Value Parameters	Applicable Level of Assembly	System	Subsystem	Equipment	Assembly	Module	Part	Function	Operational Mode	Applicable Location	Organization	Field	Depot	Factory
Design														
Operational Profile														
Reliability														
Maintainability Downtime (Max) Repair Rate														
Fault Isolation Built-in Test Special(External) GFE														
Personnel - Skill Availability														
Installation														
Environmental Capability														
Storeability														
Vulnerability														
Military Specifications														
Other														
Deployment Life														

FIGURE 2(a)

System Value Parameters	Applicable Level of Assembly	System	Subsystem	Equipment	Assembly	Module	Part	Function	Operational Mode	Applicable Location	Organization	Field	Depot	Factory
<u>Operational</u>														
Support Profile														
Self-Sufficiency														
Operational Readiness														
Replacement Level of Assembly														
Personnel-Skill Availability														
Facilities														
Utilities														
Logistic Transportation														
<u>System Utilization</u>														
Scheduled Operational Training Service														
Unscheduled Service														
Attrition														

FIGURE 2(b)

analyzing, demonstrating, and documenting required system operational capability. Tables 1 and 2 show application of some such specifications.

For accomplishment of necessary tradeoffs among development, production, and operational costs, the contractor must be furnished information upon which to base production run potential and certain operational cost factors, as indicated in appendix IV.

A further requirement to assure a minimum cost sys em is that the Government furnish information relative to areas of potential risk in system development.

Such risks can be financial or technical in nature. Areas of technical risk are determined in observation of system requirements in comparison with technology state-of-the-art. This information and that of potential cost risk is a natural by-product of the analysis to establish cost goals.

The contract type anticipated as a result of selection of a proposed alternative has some influence upon cost evaluation. The Government is responsible for considering contractual characteristics in the selection of the winning alternative.

3.1.1 CONTRACTUAL ASPECTS OF COST

Contract types currently in use can be classified into "Fixed Price" and "Cost Reimbursement" categories.

If a "Fixed Price" contract is to result, the acquisition cost is fixed for the contractually defined system. Anticipation of a "Cost Reimbursement" contract limits the credibility of proposal acquisition cost, because of lack of positive control. In consequence of this, cost evaluation of a system proposed for this type of contract requires analysis of system characteristics generating cost, and analysis of experienced relative cost efficiencies of the contractors. In support of a cost type proposal, the contractor must be required to furnish a sufficiently detailed description of system characteristics for the Government to make its own estimate of acquisition cost. The effect of contract incentive provisions can be anticipated. In the case of cost reduction incentives, acquisition cost should not incorporate expectancy of cost reduction, and the competitors should be so advised. This encourages minimum base price.

DESIGN PARAMETER	APPLICABLE SPECIFICATION	GENERAL SPECIFICATION DESCRIPTION
Reliability	MIL-R-27542 MIL-R-26674	Establishes requirements for comprehensive reliability program.
	AFR 80-5 & AFSCR 80-1	Establishes quantitative reliability requirements.
	MIL-R-27070	Covers general reliability procedures and criteria for use during development phase for ground electronic equipment. Details minimum reliability requirements to be met and demonstrated.
	MIL-STD-441	Establishes a standard procedure to insure required inherent reliability.
	MIL-HDBK-217	Describes the techniques for estimating reliability and establishing design requirements.
Availability	MIL-W-9411	Requires the development of a mathematical model of effectiveness (probability of performing a successful mission).
Maintainability	MIL-M-26512	Describes the discipline to assure design for maintainability.
Safety	MIL-S-38130	Prescribes a comprehensive system safety engineering effort through the establishment of a plan and detailed analysis efforts.
Capability	MIL-D-9310	Establishes the requirements for contractor furnished engineering analysis data.
	MIL-D-9412	Establishes the requirements for engineering data covering aspects of logistics support and operational integrity.

TABLE 1 GENERAL SPECIFICATIONS

2

If the proposals incorporate technical incentive clauses, such as for reliability, maintainability, etc., the base system and its price should define the system to be evaluated. Terms of an incentive clause should be patterned after the parameter's contribution to system value, as defined in section 2.2., that is, a change in the system's probability of accomplishing its function, multiplied by the value of the function.

For example, if a change in Mean-Time-Between-Failures from 200 hours to 250 hours increases the probability of accomplishing the function by 10 percent, and the value of the function is established at $10,000., this improvement is worth not more than 10 percent of $10,000., or $1,000.

3.2 INDUSTRY RESPONSIBILITIES

The contractor's responsibility is to analyze the requirements of the work statement, and develop a system configuration which meets the minimum constraints of performance parameters, at least cost. What this amounts to is pairing feasible design and support alternatives and selecting the least cost pair meeting the performance requirements. Figure 3 depicts the range of possible combinations of design alternatives and associated support policies to be compared. To this end, value and cost goals are allocated within deliverable end items. The general steps of the analysis follow:

PROCEDURE	SOURCES OF DESIGN/SUPPORT ALTERNATIVE
STEP 1 Devise system to meet mission requirements.	a. Determine applicable performance and cost constraints. b. A feasible alternative satisfies conditions imposed in (a).
STEP 2 Transform system functions into item packages.	a. Determine operational constraints and performance requirements for the system and develop required functions. b. From Step 2 and (a) establish hardware which will meet or exceed operational and/or performance requirements.

NOTE: There may be many alternate ways of packaging the system functions. These alternatives may extend from micro-electronics

DESIGN PARAMETER	EQUIPMENT ENVIRONMENT						EQUIPMENT LEVEL
	AIRBORNE	GROUND	GUIDED MISSILES	TEST EQUIPMENT	TRAINING EQUIPMENT	BALLISTIC MISSILE	
Capability	MIL-E-5400 MIL-I-006051 MIL-I-006051 MIL-I-8700 MIL-Q-19614 MIL-STD-202 MIL-STD-210 MIL-Q-21549	MIL-E-4158 MIL-E-4970 MIL-STD-202 MIL-STD-210 MIL-Q-21549	MIL-E-8189 MIL-E-0025366 MIL-STD-202 MIL-STD-210 MIL-Q-21549	MIL-T-945 MIL-T-18306 MIL-T-21200 MIL-STD-202 MIL-STD-210 MIL-Q-21549	MIL-T-4860C MIL-STD-202 MIL-STD-210 MIL-Q-21549		GENERAL SYSTEM SUBSYSTEM EQUIPMENT COMPONENT MODULE PART GENERAL
Reliability	MIL-D-9310 MIL-Q-19614 Spec. Bul. No. 506 MIL-STD-441	MIL-STD-441	MIL-STD-441	MIL-STD-441	MIL-STD-441	MIL-STD-441 Exhibit 58-10	SYSTEM SUBSYSTEM EQUIPMENT COMPONENT MODULE PART GENERAL
Maintainability	MIL-D-9310 MIL-Q-19614 MIL-STD-415	MIL-STD-415	MIL-T-26046 MIL-STD-415	MIL-STD-415	MIL-T-26046 MIL-STD-415		SYSTEM SUBSYSTEM EQUIPMENT COMPONENT MODULE PART GENERAL
Availability	MIL-W-9411	MIL-W-9411	MIL-W-94[illegible]	MIL-W-9411			SYSTEM

TABLE 2 - MILITARY SPECIFICATION APPLICABILITY

2

DESIGN ALTERNATIVES

Support Alternatives

	A	B	C	D	E	F	G
a							
b							
c							
d							
e							
f							
g							

Figure 3. Design/Support Alternatives

to conventional parts to distinctly different types of subsystem composition. In general, however, there will be relatively few practical alternatives.

STEP 3

Develop feasible support structure.	a.	Determine applicable constraints and requirements of support structure.
	b.	A feasible support structure satisfies conditions imposed in (a).

STEP 4

Assign Air Force Skill Category (AFSC) and manning to item packages by maintenance location.	a.	Equipment(s) and sub-assembly levels are assigned Air Force Skill Category (AFSC) by potential location of maintenance.
	b.	Manning is established for each permissible equipment/sub-assembly allocation to repair location (i.e., maintenance echelon, organization, field, depot).

NOTE: The AFSC constitutes a general personnel classification that will permit latitude for equipment classification assignment. Generally, this will not be a problem source in the generation of alternatives.

STEP 5

Select feasible design configuration for an item package.	a.	There are assumed to be several feasible configurations.

NOTE: A feasible design is a complete packaging definition of the equipment package under consideration. Thus, theoretically any change in configuration definition would produce alternatives.

STEP 6

Evaluate (eliminate) alternative design configurations.	a.	This evaluation is always with respect to the selected equipment package, and at all times, it is the entire package under evaluation.

NOTE: Caution must be exercised to ensure that the alternatives produce demonstrable differences. Many potential design changes will not provide real alternatives in that they do not generate cost differences.

STEP 7

Reiterate Steps 2-6 for other feasible alternatives.

a. Caution must be excercised to ensure that the equipment associated with a previously evaluated equipment package, i.e., if all equipment packages are added, the sum constitutes the total hardware package of the system.

Appendix V contains an iterative procedure for systematically evaluating alternatives in the U. S. Air Force support environment. Successively evaluate design/support configuration alternatives. All design/support alternatives must meet or exceed the minimum acceptable performance requirements. Cost differences between alternatives will appear as acquisition and/or operation-support cost. The areas where these potential differences would appear are listed in cost monitoring tabular form. These tables, referred to below, contain elements and serve two purposes. They provide a check list for indicating possible hidden and redundant cost sources, and also serve as work sheets for analysis.

The general mechanics of value/cost goal analysis involves four steps:

a. Use table 4 for identifying acquisition and support cost elements, as a check list for identifying differences between cost alternatives.
b. Use equations of the cost estimating technique in section 4 to establish the difference in cost magnitude between alternatives.
c. Use figure 5 of cost decision elements for determining aggregate cost effect between alternatives.
d. Use procedure developed in section 5 for cost monitoring and selection of tradeoff areas.

4. TOTAL COST MODEL

4.1 General - The total cost (T) of a system, equipment, can be represented by:

$$T = A+S, \tag{10}$$

where

A = the cost of acquisition,

S = the cost of operation and support.

The cost S is based on the expected lifetime cost. Figure 4 shows the basic cost model which has to be evaluated. Each element would ordinarily be evaluated to obtain the total cost. For purposes of reaching a decision on whether to accept a particular alternative, differences in total cost are employed. Thus, it is unnecessary to evaluate equivalent elements of the two alternatives when considering which one of two to choose. It is necessary only to evaluate the elements that are pertinent to a particular decision.

Let

T_1 = total cost of the first alternative.

T_2 = total cost of the second alternative.

the difference in total cost ($\Delta T_{2,1}$) is represented by

$$\Delta T_{2,1} = T_2 - T_1, \tag{11}$$

where elements of cost common to the first and second alternatives need not be considered if they are equal. If the quantity $\Delta T_{2,1}$ is negative, it means that the second alternative is less costly. If positive, it means that the first alternative is the correct choice, viz., less costly.

When two alternatives have been compared, the one yielding the lesser cost advantage is dropped from further consideration. Successive alternatives are devised and matched against the current alternative that has greater cost advantage.

In order to make the evaluations above, certain basic information must be available. This information involves the detail

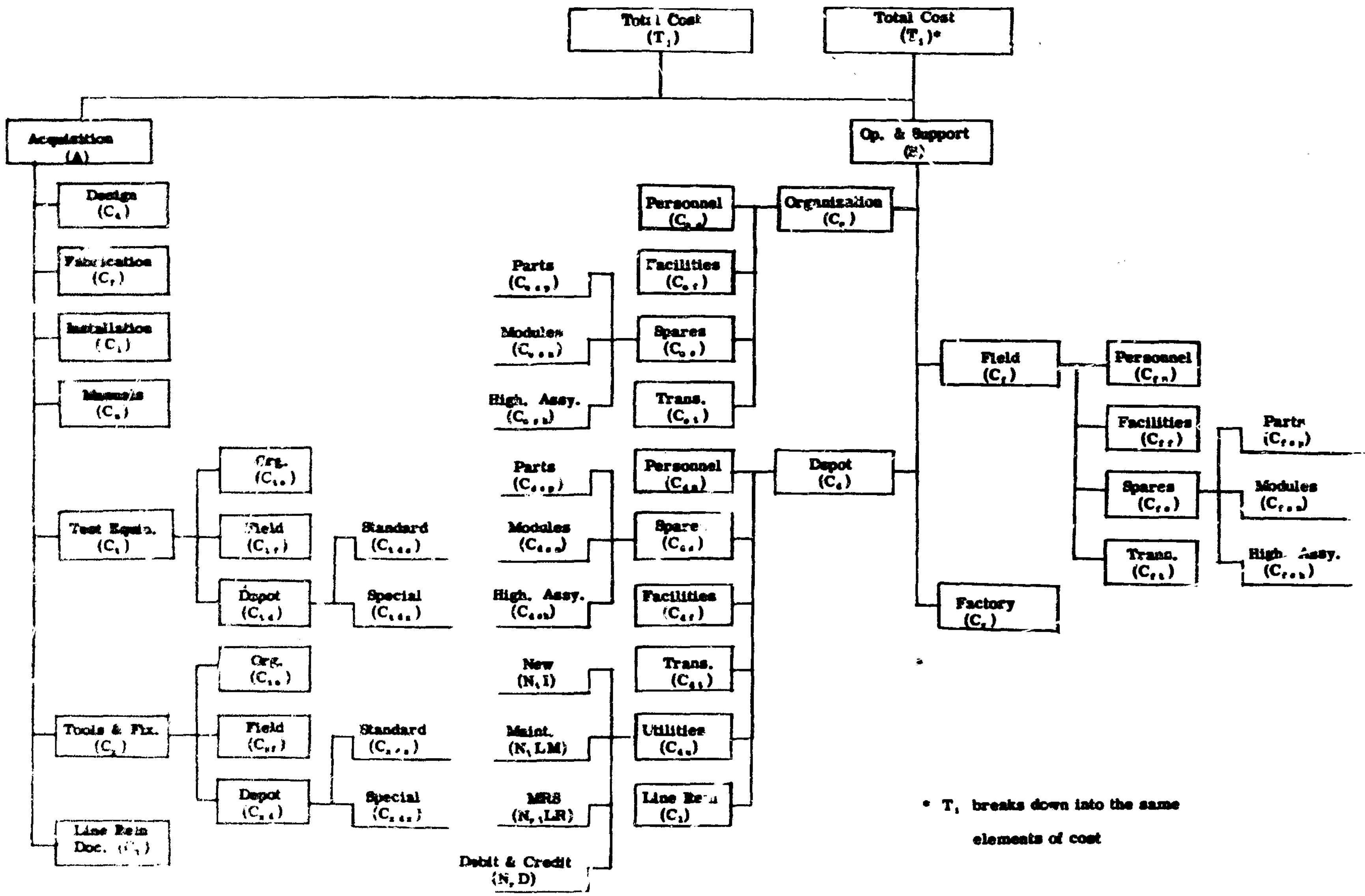

FIGURE 4. COST MODEL

acquisition and support cost elements, and associated responsibility for generation, i.e., the contractor or the Government. The estimation of support cost as well as certain acquisition costs requires additional information which permits extrapolation of basic cost elements into expected total cost differences; this information is designated as operational factors.

Table 3 contains an overview of cost factors associated with acquisition and Operation-Support, along with responsibility for providing necessary information. Also included is a detailed listing of operational factors which must be supplied (determined, estimated) in order to translate acquisition cost elements, as well as support cost elements, into total expected cost differences.

The total expected cost model incorporates certain specific techniques required to generate support cost and/or performance changes as a result of a specific alternative. The techniques are either in the detailed cost breakout, or appropriately referenced to the applicable appendix containing detail procedures.

Table 4 contains a listing of information, along with responsible sources, which will be required to be furnished by both the contractor and the Government. This information will serve as inputs to the mathematical model. The table also designates the outputs of the model which will be required for alternative evaluations.

The columns designated "Performance" and "Constant" indicate, respectively, whether the information element is a constant (as in the case of certain inventory costs), and whether it is related to the system value parameters.

4.2 DETAIL COST ELEMENTS

4.2.1 Cost of Acquisition The elements of acquisition cost to be considered include all charges which may arise from the design, development, fabrication, and installation of the equipment.

Particular attention should be paid to items which mark the differences between otherwise similar alternatives. Among these may be:

TABLE 3

TOTAL COST ELEMENTS

ACQUISITION COSTS

COST FACTOR	SYMBOL	SOURCE: GOVERNMENT	SOURCE: CONTRACTOR	SOURCE: CONSTANT
Design (R & D)	c_d		X	
Fabrication/GFE	c_f	X	X	
Installation/GEEIA	c_i	X	X	
Manuals	c_m		X	
Line Item Document	c_l		X	
Test Equipment	c_t		X	
Organizational	c_{to}		X	
Field	c_{tf}		X	
Depot	c_{td}		X	
Standard	c_{tds}		[illegible]	
Special	c_{tdx}		X	
Tools & Fixtures	c_x		X	
Organizational	c_{xo}		X	
Field	c_{xf}		X	
Depot	c_{xd}		X	
Standard	c_{xds}		X	
Special	c_{xdx}		X	
OPERATIONAL FACTOR				
Type $_i$ item cost (production quantity)	(c_i)		X	
Type $_i$ item Failure Rate	(λ_i)		X	
Type $_i$ item Repair Rate	(μ_i)		X	
Number Type $_i$ item in equipment	(n_i)		X	
Number of demands for factory support	N_{fy}		X	
Equipment Restore Time (hours)	MTTR		X	
Unreadiness Due to: 1. Sparing 2. Personnel	u		X	
Equipment Life	[illegible]	X		
Number of equipments scheduled for operation	E	X		
Number of Equipments per site	N	X		

TABLE 3 (CONT.)

TOTAL COST ELEMENTS

ACQUISITION COSTS

OPERATIONAL FACTOR	SYMBOL	SOURCE: GOVERNMENT	SOURCE: CONTRACTOR	SOURCE: CONSTANT
Equipment operational time per hr		X		
Equipment operational readiness goal	(1-u)			
Equipment reliability	MTBF	X		
Number of field shops	F_s	X		
Equipment phase out period	L_p	X		
Number of organization sites	Y	X		

OPERATIONAL AND SUPPORT COSTS

COST FACTOR	SYMBOL	GOVERNMENT	CONTRACTOR	CONSTANT
Personnel: (Technical Manpower)				
Organizational	C_{om}	X		
Field	C_{fm}	X		
Depot	C_{dm}	X		
Facilities: (Utilities & Materials for Maintenance and test equipment)				
Organizational	C_{of}	X		
Field	C_{ff}	X		
Depot	C_{df}	X		
Transportation				
Organizational	C_{ot}	X		
Field	C_{ft}	X		
Depot	C_{dt}	X		
Spares				
Organizational	C_{os}	X		
Parts	C_{osp}	X		
Modules	C_{osm}	X		
Higher Assembly	C_{osh}	X		
Field	C_{fs}	X		
Parts	C_{fsp}	X		
Modules	C_{fsm}	X		
Higher Assembly	C_{fsh}	X		

TABLE 3 (CONT .)

TOTAL COST ELEMENTS

OPERATIONAL AND SUPPORT COSTS SOURCE

COST FACTOR	SYMBOL	GOVERNMENT	CONTRACTOR	CONSTANT
Depot	C_{ds}	X		
Parts	C_{dsp}	X		
Modules	C_{dsm}	X		
Higher Assembly	C_{dsh}	X		
Utilities (Depot)	C_{du}	X		
Line Item (Depot)	C_l	X		
New	N_l	X		
Maintenance	N_{lLM}	X		
MRS.	N_{rLR}	X		
Debit and Credit	N_{rD}	X		
Factory (all factors)	C_y			

TABLE 4

SOURCES OF INFORMATION

(a) GOVERNMENT PROVIDED INFORMATION

		PRODUCT COST			
	SYMBOL	ACQUISITION	SUPPORT	CONSTANT	PERFORMANCE
Line Item entry/maintenance	C_i				
Quantity newly introduced	N_i		X		
Cost per new item entry	I		X	X	
Maintaining item in stock	M		X	X	
On Master Repair Schedule (MRS)	R		X	X	
Quantity of stock item repair Debit and Credit	D		X	X	
Equipment life	L				
Number of equipments scheduled for operation	E				
Equipments per site	N				
Number of sites/Field Shops	Y/F				
Equipment Permissible Unreadiness (Specified)	u				X
Equipment Downtime Allowable (Specified)	D_t				X
Equipment Maintainability Allowable (Specified)	MTTR				X
Equipment Reliability Allowable (Specified)	MTBF				X
Information Requirements for Proposal Preparation Procedures					
Equipment Phase-out Period	L_s				
Number skill types of quantity assignable	G_{ijk}				X
Personnel per site					X
Maximum					X
Minimum					X
Utilization Factor (Maintenance)	P				X
Personnel Turnover Rates				X	
Personnel Utilization (Operation)					X

TABLE 4 (CONT.)

(a) GOVERNMENT PROVIDED INFORMATION

FACTOR	SYMBOL	PRODUCT COST: ACQUISITION	PRODUCT COST: SUPPORT	PRODUCT COST: CONSTANT	PERFORMANCE
Personnel Utilization (Maintenance)					X
Quantity					X
Skill					X
Operational Schedule					X
Preventive Maintenance (Specified)					X
Organizational (Hours)					X
Field (Hours)					X
Depot (Hours)					X
By Task:					
Periodicity					X
Duration					X
Equipment Characteristics (specified)					X
Weight					X
Volume					X
Power					X
Transportation cost/shipment	$\bar{C}_{fto}$				
	$\bar{C}_{dtf}$				
	$\bar{C}_{ato}$				
(HQ AFLC/code SGT/) Military	$\bar{C}_{dtf}$				
Commercial	$\bar{C}_{dtf}$			X	

TABLE 4 (CONT.)

SOURCES OF INFORMATION

(b) CONTRACTOR-PROVIDED INFORMATION

FACTOR	SYMBOL	PRODUCT COST ACQUISITION	SUPPORT	CONSTANT	PERFORMANCE
Design (Research & Development)	c_d	X			
Fabrication/GFE	c_f	X			
Installation/GEEIA	c_i	X			
Manuals	c_m	X			
Line Item Documentation	c_l	X			
Test equipment:Type per location	c_t	X			
Organizational	c_{to}	X			
Field	c_{tf}	X			
Depot	c_{td}	X			
Standard (Contractor/GFE)	c_{tds}	X			
Special	c_{tdx}	X			
Tools & Fixtures:(Type per location	c_x	X			
Organizational	c_{xo}	X			
Field	c_{xf}	X			
Depot	c_{xd}	X			
Standard (Contractor/GFE)	c_{xds}	X			
Special (Contractor/GFE)	c_{xdx}	X			
Type i item (spare parts, modules, and high assembly)	(c_i)	X			
Type i item failure rate	(λ_i)				X
Type i item repair rate	(μ_i)				X
Number of type item in equip.	(n_i)				X
Total number of failures over equipment life	N_y				X
Number of demands for factory support	N_{fy}				
Factory support (total)	c_y	X			
Equipment Reliability and Maintainability	MTBF, λ MTTR, μ				X
Unreadiness Due to:					
Inherent Limit	$\frac{\lambda}{\mu}$				
Spares Allocation, Manning Allocation	u				X

TABLE 4 (CONT.)

(c) INFORMATION PROVIDED BY MODEL

FACTOR	SYMBOL	PRODUCT COST ACQUISITION	SUPPORT	CONSTANT	PERFORMANCE
Unreadiness	n				X
Personnel: (Direct/Indirect					
technical Manpower	C_m		X		X
Organizational	C_{om}		X		X
Field	C_{fm}		X		
Depot	C_{dm}		X		
Facilities: (Utilities/material					
for operation and maintenance	C_f		X		
Organizational	C_{of}		X		
Field	C_{ff}		X		
Depot	C_{df}/C_{du}		X		
Transportation:	C_t		X		X
Organizational	C_{ot}		X		
Field	C_{ft}		X		
Depot	C_{dt}		X		
Spares:	C_s		X		X
Organizational	C_{os}		X		
Parts	C_{osp}		X		
Modules	C_{osm}		X		
Higher Assembly	C_{osh}		X		
Field	C_{fs}		X		
Parts	C_{fsp}		X		
Modules	C_{fsm}		X		
Higher assembly	C_{fsh}		X		
Depot	C_{ds}		X		
Parts	C_{dsp}		X		
Modules	C_{dsm}		X		
Higher Assembly	C_{dsh}		X		
Line item processing (Depot)	C_l		X		
Introducing new	N_l T		X	X (I)	
Retaining item in stock	N_l LM		X	X (M)	
Retaining item on NRS	N_r LR		X	X (R)	
Debit and Credit	N_r D		X	X (D)	
Factory cost (when applicable)	C_y		X		

a. Built-in fault isolation features.

b. Special test equipment.

c. Special tools.

d. Facility of manufacture.

Differences in research, development, design, or hardware costs should be considered where they constitute a significant difference among the alternatives. Differences in requirements for Government-furnished equipment (GFE) should also be established. In any case, refined estimates of costs are justified only when the alternative, or group of alternatives, has cost or other advantages which make it a good candidate for selection.

Cost of acquisition (A) can be represented by:

$$A = c_d + c_f + c_i + c_m + c_t + c_x + c_l \quad (12)$$

where

c_d = cost of design,

c_f = cost of fabrication,

c_i = cost of installation,

c_m = cost of manuals,

c_t = cost of test equipment,

c_x = cost of tools and fixtures, and

c_l = cost of line item documentation.

4.2.1.1 - Cost of Design - The cost of design is

$$c_d = c_{de} + c_{dm} + c_{ds} + c_{da} \quad (13)$$

where

c_{de} = cost of electrical design,

c_{dm} = cost of mechanical design,

c_{ds} = cost of engineering support, and

c_{da} = cost of Product Assurance.

4.2.1.2 Cost of Fabrication - The cost of fabrication is represented

$$C_f = c_{fe}+c_{fa}+c_{fi}+c_{fs}+c_{fm}+c_{ft}+c_{fq}+c_{fp} \tag{14}$$

where

c_{fe} = cost of manufacturing engineering,

c_{fa} = cost of assembly,

c_{fi} = cost of inventory,

c_{fs} = cost of shipping/receiving,

c_{fm} = cost of model and machine shops,

c_{ft} = cost of test engineering,

c_{fq} = cost of quality control, and

c_{fp} = cost of purchasing.

4.2.1.3 Cost of Installation - The cost of installation can be broken into

$$c_i = c_{ip}+c_{is}+c_{it}+c_{ir}+c_{is}+c_{if} \tag{15}$$

where

c_{ip} = cost of prototype installation,

c_{is} = cost of service model installation,

c_{it} = cost of training,

c_{ir} = cost of repair program,

c_{is} = cost of spares provisioning, and

c_{if} = cost of field support.

4.2.1.4 Cost of Manuals - The cost of manuals includes

$$c_m = c_{mp} + c_{mu} \tag{16}$$

where

c_{mp} = cost of producing manuals, and

c_{mu} = cost of updating,

4.2.1.5 Cost of Test Equipment - The costs of test equipment can be further broken down as follows:

$$c_t = c_{to} + c_{tf} + c_{td} \tag{17}$$

and

$$c_{td} = c_{tds} + c_{tdx} \tag{18}$$

where

c_{to} = cost of test equipment at organization,

c_{tf} = cost of test equipment at field,

c_{td} = cost of test equipment at depot,

$c_{td} = c_{tds} + c_{tdx}$

c_{tds} = cost of standard test equipment at depot, and

c_{tdx} = cost of special test equipment at depot.

4.2.2 Cost of Operation and Support - The cost of operation and support (S) is represented by

$$S = c_o + c_f + c_d + c_y \tag{19}$$

where

c_o = cost at organization,

c_f = cost at field,

c_d = cost at depot, and

c_y = cost at factory.

4.2.2.1 <u>Cost at Organization</u> - All operational costs are included with the support costs at organization. The cost at organization (c_o) is represented by

$$c_o = c_{om} + c_{of} + c_{os} + c_{ot} \tag{20}$$

where

c_{om} = cost of personnel,

c_{of} = cost of facilities,

c_{os} = cost of spares, and

c_{ot} = cost of transportation.

4.2.2.1.1 <u>Cost of personnel</u> - The cost of personnel is represented by

$$c_{om} = (\sum_i \sum_j \sum_k G_{ijk} X_{ijk}) + F \tag{21}$$

where

G_{ijk} = number of men with skill i, in skill field k, in an operation and maintenance unit j,

X_{ijk} = average expense incurred by the government as a result of the manning with skill i in skill field k, in unit j, and

F = the administrative and service costs normal to an operating and maintenance unit of size

$\sum_i \sum_j \sum_k G_{ijk}$

The values of these variables are found as follows:

a. G_{ijk} is the number of men with skill i, skill field k, in operations and maintenance unit j, and is determined by a manning analysis. See Appendix III.

b. X_{ijk}, see under personnel cost in Appendix VIII.

c. ., for small relative changes in $\sum\sum\sum G_{ijk}$, the difference in F is practically insignificant.

4.2.2.1.2 <u>Cost of Facilities</u> - The cost of facilities (c_{of}), including utilities, is represented by

$$c_{of} = c_{ofu} + c_{ofm} + c_{oft} \tag{22}$$

Normally, demonstrable differences in these costs will not exist among alternatives, and for this reason, such costs can be neglected; or, in many cases, they will cancel out when differential costs are considered. Where they are neither, estimates should be made using the best available information. (The buildings, power generators, test equipment, and similar items, are acquisition costs, if chargeable). These costs may be treated as follows:

c_{ofu} = cost of utilities (power). It is necessary to estimate total power for equipment, air-conditioning, etc. Where power is generated on site, use delivered cost of fuel. Otherwise, use KWH rates for commercial sources. Include the cost of power (fuel) for operation.

c_{ofm} = cost of materials for maintenance of facilities. It is necessary to estimate the total cost of upkeep using as sources, the civil engineering site function.

c_{oft} = cost of materials for maintenance of test equipment. This cost is to be assessed in the same manner as the operating equipment and in conjunction with it where there is a commonality between parts.

4.2.2.1.3 <u>Cost of Spares</u> - The actual number of spare items, of all types, is established by using an optimizing technique. The principle of the technique is to chose the one alternative from many, which returns maximum reduction in unreadiness per unit cost invested. See appendix VI, Logistic Criteria and Methods for Establishing Spares Levels.

The general equation representing cost of spares at Organization is

$$c_{os} = c_{osp} + c_{osm} + c_{osh} \tag{23}$$

where

c_{osp} = cost of parts,

c_{osm} = cost of modules, and

c_{osh} = cost of higher assemblies.

4.2.2.1.4 <u>Cost of Parts</u> - Let the cost of parts (c_{osp}) be represented by the following equation:

$$c_{osp} = LE\sum_i c_{i-p} n_{i-op} \lambda_{i-p} \quad (24)$$

and

$$= N_{r-po} \bar{c}_p$$

where

L = Life of equipment,

E = number of equipments scheduled for operation,

n_{i-p} = number of part i per equipment,

c_{i-p} = cost of part i,

λ_{i-p} = usage rate of part i,

N_{r-po} = total parts repair demands (usage)-organization

$= LE\Sigma n_{i-op} \lambda_{i-p}$ and

$\bar{c}_p$ = mean cost of part.

The total demands for repair based on part count is given by

$$N_r = LE\Sigma N_{i-p} \lambda_{i-p}. \quad (25)$$

The number of part replacements at organization level is given by

$$N_{r-po} = LE\Sigma N_{i-op} \lambda_{i-p} \quad (26)$$

where n_{i-op} = number of part applications in assemblies for which organization has repair responsibility.

Similarly, for field and depot,

$$N_{r-pf} = LE\Sigma N_{i-fp} \lambda_{i-p} \quad (27)$$

$$N_{r-pd} = LE\Sigma N_{i-dp} \lambda_{i-p}$$

and

$$N_r = N_{r-po} + N_{r-pf} + N_{r-pd}.$$

When usage information is missing, λ_{i-p} is found by the following:

$$\lambda_{i-p} = 3\lambda^{*}_{i-pf} \qquad (28)$$

where

λ_{i-pf} = predicted failure rate of the part i.

For high demand systems, part cost over the equipment lifetime will closely approximate this expression, and will not usually contribute significant unreadiness. For low demand systems, it will generally be necessary to derive part cost through optimizing procedures (detailed in appendix VI).

4.2.2.1.5 Cost of Modules - The cost of modules at organization is represented by

$$C_{o s s} = \sum_i S_{i-so} c_i \qquad (29)$$

where

S_{i-so} = number of modules of type i, used and on hand at the time of phase-out, at organization to maintain a pre-established level of permissible unreadiness,

S_{i-so} = S [support alternative, $u(\mu,\lambda)$], reference appendix III, appendix VI.

where

u = unreadiness, and

c_i = cost of module of type i.

The usage rate is approximately equal to the failure rate for the module case.

*See Appendix VIII for parts usage constant.

4.2.2.1.6 **Cost of Higher Assemblies** - **The cost of higher assemblies, at organization, is**

$$c_{osh} = \sum_{i} S_{i-ho} \cdot c_i \tag{30}$$

where

S_{i-ho} = number of higher assemblies, of type i used, and on-hand at time of phase-out, at the organization to maintain a pre-established level of permissible unreadiness,

S_{i-ho} = cost of higher assembly of type i.

4.2.2.1.7 Cost of Transportation - The transportation costs at organization (c_{ot}) are determined in the following manner:

(a) From on site operational location to and from on site field maintenance shop by routine methods (generally negligible cost).

(b) c_{fto} = site operational . . . . by priority requisition = (demands) x (average length of round trip) x (cost per trip (Government Data Input))

(c) c_{dto} = site operational . . . . from depot maintenance (4.2.3.4).

(d) Vehicles on which equipment is mounted should be included in acquisition costs, whether Government-furnished equipments or contractor-supplied.

4.2.2.2 Cost at Field - The cost at field (c_f) is represented by

$$c_f = c_{fs} + c_{fi} + c_{fs} + c_{ft} . \tag{31}$$

4.2.2.2.1 Cost of Personnel - The cost of personnel at field (when distinct of organization) (c_{fs}) is

$$c_{fs} = \left(\sum_{ijk}\sum\sum G_{ijk} X_{ijk}\right) + F \tag{32}$$

where the symbols, on the right side of the equation, are defined in paragraph 4.2.2.1.1 Field personnel may be considered as independently contributing unreadiness (see examples of Appendix III).

4.2.2.2.2 <u>Cost of Facilities at Field</u> - In determining cost of facilities at field (c_{ff}), use procedures in 4.2.2.1.2.

4.2.2.2.2.1 <u>Cost of Spares at Field</u> - The cost of spares at is expressed as

$$c_{fs} = c_{fsp} + c_{fsm} + c_{fsh} \tag{33}$$

where

c_{fsp} = cost of parts,

c_{fsm} = cost of modules, and

c_{fsh} = cost of higher assemblies.

4.2.2.2.2.2 Cost of Parts - The cost of parts at field (c_{fsp}) is

$$c_{fsp} = N_{r-pf}\bar{c}_p \tag{34}$$

where

N_{r-pf} = total parts repair demands-field.

4.2.2.2.2.3 <u>Cost of Modules</u> - The cost of modules at field is

$$c_{fsm} = \sum_i S_{i-sf} c_i \tag{35}$$

where

S_{i-sf} = number of modules, of type i, used and on hand at the phase-out period, at field to maintain a pre-established level of permissible unreadiness,

S_{i-sf} = S [support alternative, u(μ,λ)] (references appendix III and appendix VI.)

4.2.2.2.2.4 <u>Cost of Higher Assemblies</u> - The cost of higher assemblies, at field, (c_{fsh}) is

$$C_{fsh} = \sum_i S_{i-hf} c_i \tag{36}$$

where

S_{i-hf} = number of higher assemblies, of type i, used and on hand at the phase-out period,

at field to maintain a pre-established level of permissible unreadiness,

S_{i-hf} = S[support alternative, $u(\mu,\lambda)$] (references appendix III and appendix VI.

4.2.2.2.3 Cost of Transportation - The cost of transportation (c_{ft}) is counted as part of organization or depot costs. (See paragraphs 4.2.2.1.7 and 4.2.2.3.4).

4.2.2.3 Cost at Depot - The cost at depot (c_d) is represented by

$$c_d = c_{ds}+c_{df}+c_{ds}+c_{dt}+c_{du}+c_l \tag{37}$$

where

c_{ds} = cost of personnel at depot,

c_{df} = cost of facilities at depot,

c_{ds} = cost of spares at depot,

c_{dt} = cost of transportation at depot,

c_{du} = cost of utilities at depot, and

c_l = cost of line item at depot.

4.2.2.3.1 Cost of Personnel at Depot - The cost of personnel at depot (c_{ds}) is represented as follows:

Let

N_{r-md} = the module repair demand at depot

$= (r_1+q_1)LE\sum_i n_{i-m}$

where r_1, q_1 are fractions of total module failure population returned from organization and field, and

N_{r-hd} = the higher assembly repair demand at depot

$=(r_2+q_2)LE\sum_i n_{i-h}\lambda_{i-h}$

where r_2, q_2 are fractions of total higher assembly failure population returned from organization and field.

Since there is essentially a constant workload at the depot, rather than the standby/work situation that exists at the field and organization, c_{ds} can be expressed as follows:

$$c_{ds} = LE\ [\sum_i (r_1+q_1)n_{i-s}\lambda_{i-s}) + (\sum_i (r_2+q_2)n_{i-}\lambda/\mu_{i-h})]c_d \qquad (38)$$

where

μ_{i-s} = mean repair rate of modules, of type i, at depot,

μ_{i-h} = mean repair rate of higher assemblies, of type i, at depot, and

c_d = cost of labor, direct and indirect*.

4.2.2.3.2 Cost of Facilities at Depot - The cost of facilities (c_{df}) is represented by

$$c_{df} = c_{dfs} + c_{ift} \qquad (39)$$

where

c_{dfs} = cost of material for maintenance of facilities at depot, and

c_{dft} = cost of material for maintenance of test equipment at depot.

The statements in paragraph 4.2.2.1.2 are applicable in evaluation of these costs.

4.2.2.3.3 Cost of Spares in Depot - The general equation representing cost of spares in depot is

$$c_{du} = c_{dsp} + c_{dsm} + c_{dsh} \qquad (40)$$

where

c_{dsp} = cost of parts,

c_{dsm} = cost of modules, and

*See appendix VIII for depot labor constants.

c_{dsh} = cost of higher assemblies.

4.2.2.3.3.1 Cost of parts - The cost of parts at depot (c_{dsp}) can be expressed as

$$c_{dsp} = LE\Sigma c_{i-p} n_{i-pd} \lambda_{i-p} \quad (41)$$

Also,

$$c_{dsp} = N_{r-pd} \bar{c}_p$$

where

N_{r-pd} = total part repair demand-depot.

(See paragraph 4.2.2.2.2.1).

4.2.2.3.3.2 Cost of Modules - The cost of modules at depot (c_{dsm}) is

$$c_{dsm} = \sum_i S_{i-md} c_i \quad (42)$$

where

S_{i-md} = number of modules, of type i, used and on hand, at the phase-out period at depot to obtain desired operational readiness for the equipment.

S_{i-md} = S [support alternative, $u(\mu,\lambda)$] (reference appendix III and appendix VI).

4.2.2.3.3.3 Cost of Higher Assemblies - The cost of higher assemblies, at depot, (c_{dsh}) is

$$c_{dsh} = \sum_i S_{i-hd} c_i \quad (43)$$

where

S_{i-hd} = number of higher assemblies, of type i, used and on hand at phase-out period at depot to maintain a preestablished level of permissible unreadiness,

S_{i-hd} = S[support alternative, $u(\mu,\lambda)$].

4.2.2.3.4 Cost of Transportation - The cost of transportation associated with depot (c_{dt}) can be expressed

$$c_{dt} = c_{dto} + c_{dtf} \qquad (44)$$

where

c_{dto} = total cost of round trips from organization to depot, and

c_{dtf} = total cost of round trips from field to depot.

This formula is evaluated by means of the following:

$$c_{dto} = [(N_{r-sd})r_1 + (N_{r-hd})r_2]\bar{c}_{dto} \qquad (45)$$

and

$$c_{dtf} = [N_{r-sd})_{q1} + (N_{r-hd})q_2]\bar{c}_{dtf}$$

where

$r_1 + q_1 = 1$, and

$r_2 + q_2 = 1$, where r_1, q_1, r_2, q_2 are as defined in 4.2.3.1.

$\bar{c}_{dto}$ = mean cost of round trip between organization and depot, and

$\bar{c}_{dtf}$ = mean cost of round trip between field and depot.

4.2.2.3.5 Cost of Utilities at Depot - The cost of utilities (c_{du}) is

$$c_{du} = c_{due} + c_{dub} \qquad (46)$$

where

c_{due} = cost of power and

c_{dub} = cost of buildings.

Normally, this cost will cancel out when taking differentials corresponding to different alternatives. If it does not, a cost analysis is required.

4.2.2.3.6 Cost of Line Item - The cost of line item (c_t) can be represented by

$$c_t = N_t [I+(L)\ (M)]+N_{rt}\ (L)(R)+(N_r)(D), \qquad (47)$$

where

N_t = member of new line item introduced into the supply system. The value of this factor is necessarily user furnished data.

I = cost of introducing a line item into the support system. The value has been determired to be approximately $34.00 per item.

L = life of equipment

M = cost per year of maintaining a line item in the supply system. The value has been determined to be approximately $19.00 per year per item.

N_{rt} = number of stock items repaired by depot. The value is furnished as user furnished data.

R = cost per year of maintaining a stock item (recoverable) in the master repair schedule (MRS). The value has been determined to be approximately $29.00 per year per item.

D = debit and credit costs associated with inventory accountability and storage for item repaird at the depot. This refers to a documentation cost, and has been determined to be approximately $14.00 per repair action.

4.2.2.4

c_y = costs at factory

In these instances where factory maintenance is planned as an integral part of the equipment maintenance/support policy, the costs connected with performing the services at factory will be approximately the same, or somewhat less, than would be incurred if the work were done at depot.

The values of M, R, D, and I, are determined by Rome Air Development Center's Technical Report 65-214. (For all these values, see appendix VIII. The values of the other parameters

are variable with the system type.

4.3 Cost Analysis Structure

The acquisition and support cost elements presented in the foregoing section may be viewed profitably as consisting of two common cost categories. These are recurring and non-recurring costs. In the following tables (5(a)-(d) and 6(a) and (b)), acquisition and support cost are identified in terms of these cost categories.

The rationale behind the breakout of both acqusition and support costs into non-recurring and recurring is that it simplifies identification of distinct cost elements, and of equal importance, it points up the significant areas of cost tradeoff (engineering and fabrication).

4.4 Cost Decision Element Matrix

In general, it will only be necessary to evaluate the difference between two alternatives; where more than two alternatives exist, the procedure is to systematically eliminate the poorerchoice alternative by direct comparison of estimated cost differences (being assured that system value parameters are satisfied by each alternative considered).

Figure 5 illustrates a tabular procedure for evaluating each element of the cost model. Provision is made, in figure 5, for the evaluation of two alternatives. Only the elements that change, from one alternative to the other, will be required. Once two alternatives have been evaluated, the one yielding a cost advantage is retained, and the other alternative is no longer considered.

		Step ( )	
Cost Element (C)	Sub-Script	A ( )	A ( )
Design	d		
Fabrication	f		
Installation	i		
Manuals	m		
Test Equipment	t		
Tools and Fixtures	x		
Line Item Documentation	l		
		S ( )	S ( )
Organization			
Personnel	o		
Facilities	om		
Facilities	of		
Spares	os		
Transportation	ot		
Field	f		
Personnel	fm		
Facilities	ff		
Spares	fd		
Transportation	ft		
Depot	d		
Personnel	dm		
Facilities	df		
Spares	ds		
Transportation	dt		
Utilities	du		
Line Item	e		
Factory	y		
Total Cost	t		
Cost Difference	t		

Figure 5 - Cost Decision Elements

2

TABLE 5 (a) - COST DECISION ELEMENTS- ACQUISITION

Costs		Non-recurring						Recurring					
Acquisition		System	Sub-sys.	Equipment	Component	Module	Part	System	Sub-sys.	Equipment	Component	Module	Part
1. Design													
Electrical	Specifications	X	X	X	X	X	X						
	Functional Design	X	X	X	X	X							
	Electronic Packaging	X	X	X	X	X							
	Inter-conn. Cable/Wiring	X	X	X	X	X							
	Debug & Evaluation	X	X	X	X	X							
	Factory Follow-Up							X	X	X	X	X	X
Mechanical	Specifications	X	X	X	X	X	X						
	Mechanical Layout	X	X	X	X	X							
	Structural Design	X	X	X	X	X							
Engineering Support	Drafting							X	X	X	X	X	X
	Reproduction							X	X	X	X	X	X
	Control File							X	X	X	X	X	X
	Eng Lab - Test Equip	X	X	X	X	X							
	Eng Lab - Envir. Equip	X	X	X	X	X							
	Eng Lab - Personnel							X	X	X	X	X	X
Product Assurance	Design Review	X	X	X	X	X							
	Part Selection & App.	X	X	X	X	X	X						
	Failure Reporting & Anal.							X	X	X	X	X	X
	Predictions & Eval.	X	X	X	X	X	X						
	Maintainability	X	X	X	X	X							
	Value Engineering							X	X	X	X	X	X
	Standards Lab. Equip.	X	X	X	X	X	X						
	Standards Lab. Oper.							X	X	X	X	X	X
	Chemical/Metal Lab							X	X	X	X	X	X

2

TABLE 5 (b) - COST DECISION ELEMENTS- ACQUISITION (Cont)

Costs		Non-recurring: System	Sub-sys.	Equipment	Component	Module	Part	Recurring: System	Sub-sys.	Equipment	Component	Module	Part
Acquisition													
2. Fabrication													
Manufacturing Eng.													
	Methods	X	X	X	X	X	X						
	Mechanization Proc.	X	X	X	X	X	X						
	Detail Process	X	X	X	X	X	X						
	Test Process	X	X	X	X	X	X						
	Equipment Maint.	X	X	X	X	X	X						
	Customer Rework							X	X	X	X	X	X
Assembly Area													
	Material Handling							X	X	X	X	X	X
	Assembly							X	X	X	X	X	
	In-process Test Labor								X	X	X	X	X
	Formal Test Labor							X	X	X	X	X	X
Inventory Control													
	Physical Invent. Adjust.							X	X	X	X	X	X
	Material Diversion Cont.							X	X	X	X	X	X
	Nuisance Mat.							X	X	X	X	X	
	Good Stores Mat.							X	X	X	X	X	X
	Reject Stores Mat.							X	X	X	X	X	X
	Termination Stores Mat.											X	X
	Controlled Store Mat.							X	X	X	X	X	X
	Mod./Surplus Mat.							X	X	X	X	X	X
	Scheduling							X	X	X	X	X	X
Shipping/Receiving													
	Receipt Handling							X	X	X	X	X	X
	Packing							X	X	X	X	X	X
	Material Handling							X	X	X	X	X	X
	Special Cont. Design							X	X	X	X	X	X
	Audit Function							X	X	X	X	X	X

2

TABLE 5 (c) - COST DECISION ELEMENTS- ACQUISITION (Cont).

Costs	Non-recurring System	Sub-sys.	Equipment	Component	Module	Part	Recurring System	Sub-sys.	Equipment	Component	Module	Part
Acquisition												
Fabrication (cont)												
Model Shop							X	X	X	X	X	X
Machine Shop							X	X	X	X	X	X
Test Engineering												
GFE Modification	X	X	X	X	X	X						
Test Procedures							X	X	X	X	X	X
Test Equip. Calib.							X	X	X	X	X	X
Test Equip. Maint.							X	X	X	X	X	X
Quality Control												
Vendor Surveillance									X	X	X	X
Purchased Mat. Insp.									X	X	X	X
Visual/Mach. Insp.							X	X	X	X	X	X
Statistical QC							X	X	X	X	X	X
Non-conformance Items							X	X	X	X	X	X
Audit							X	X	X	X	X	X
Purchasing												
Subcontract Services			X	X	X	X						
Intercorporate Services			X	X	X	X						
Advances to Subcontract.			X	X	X	X						
Purchased Services									X	X	X	X
3. Installation												
Prototypes Models	X	X	X	X	X							
Service Models	X	X	X	X	X							
Training	X	X	X	X	X	X						
Repair Program Eval.	X	X	X	X	X	X						
Spare Parts Prov.	X	X	X	X	X	X						
Field Support Proj.	X	X	X	X	X	X						
4. Manuals												
Technical Manual	X	X	X	X	X	X						
Manual Updating							X	X	X	X	X	X

TABLE 5 (d) - COST DECISION ELEMENTS - ACQUISITION (Cont).

Costs / Acquisition	Non-recurring: System	Sub-Sys.	Equipment	Component	Module	Part	Recurring: System	Sub-sys.	Equipment	Component	Module	Part
5. Test Equipment												
Organization			X	X	X	X						
Field			X	X	X	X						
Depot												
Standard			X	X	X	X						
Special			X	X	X	X						
Factory												
Standard			X	X	X	X						
Special			X	X	X	X						
6. Tools, Fix., & Jig.												
Organization			X	X	X							
Field			X	X	X							
Depot												
Standard			X	X	X							
Special			X	X	X							
Factory												
Standard			X	X	X	X						
Special			X	X	X	X						
7. Line Item Doc.	X	X	X	X	X	X						

2

TABLE 6 (c) - COST DECISION ELEMENTS - SUPPORT

Costs Support	Non-recurring System	Non-recurring Sub-sys.	Non-recurring Equipment	Non-recurring Component	Non-recurring Modules	Non-recurring Part	Recurring System	Recurring Sub-Sys.	Recurring Equipment	Recurring Component	Recurring Module	Recurring Part
1. Organization												
Personnel							X	X	X	X	X	X
Facilities												
Utilities							X	X	X	X	X	X
Material for Maint.							X	X	X	X	X	X
Material for Test Equip.							X	X	X	X	X	X
Spares												
Parts							X	X	X	X	X	X
Modules							X	X	X	X	X	X
Higher Assemblies							X	X	X	X	X	X
Transportation							X	X	X	X	X	X
2. Field												
Personnel							X	X	X	X	X	X
Facilities												
Utilities							X	X	X	X	X	X
Material for Maint.							X	X	X	X	X	X
Material for Test Equip.							X	X	X	X	X	X
Spares												
Parts							X	X	X	X	X	X
Modules							X	X	X	X	X	X
Higher Assemblies							X	X	X	X	X	X
3. Depot												
Personnel							X	X	X	X	X	X
Facilities												
Materials for Maint.							X	X	X	X	X	X
Spares												
Parts							X	X	X	X	X	X
Modules							X	X	X	X	X	X
Higher Assemblies							X	X	X	X	X	X

2

TABLE 5 (b) - COST DECISION ELEMENTS - SUPPORT (Cont.)

Costs			Non-recurring						Recurring					
Support			System	Sub-sys.	Equipment	Component	Module	Part	System	Sub-sys.	Equipment	Component	Module	Part
Depot (cont.)	Transportation	Organization							X	X	X	X	X	X
		Field							X	X	X	X	X	X
	Utilities	Power							X	X	X	X	X	X
		Buildings	X	X	X	X	X	X						
	Line Item	New	X	X	X	X	X	X						
		Maintenance							X	X	X	X	X	X
		MRS							X	X	X	X	X	X
		Debit & Credit							X	X	X	X	X	X
4. Factory									X	X	X	X	X	X

2

5. TIME PHASED VALUE METHODOLOGY

5.1 Technique Philosophy - The basic rationale of the value allocation review technique consists of directing the sellers to cost and value goals which will make them more competitive through cost consciousness, based on increased awareness of procurement item requirements and the competitive environment. Basically, the technique presumes competitive behavior of the seller in a dynamic situation of increasing information concerning both product requirements and competitive environment.

Given a value incentive goal, the potential seller will have the capability of using the following strategy:

a. He will assume that he is in a position to repeat or outperform his previous cost position, because of the additional insight gained in past performance.

b. He will direct himself t development of cost structure compatible with the value goals.

This cost structure must be directed to a cost at or below the buyer's cost allocation targets, if the seller expects to remain competitive. The result of the buyer's specifying a cost goal is to shift the mean amount of the total cost responses toward a lower cost. Additionally, the magnitude of cost difference between the cost allocation target established by the buyer and that established by the seller will be heavily dependent upon the seller's known competition. Thus, the seller must direct himself to establishing a cost goal which will be below that of his competitors. Recognizing that his competitors are striving to achieve the contract award, his cost goal must be predicated additionally, on the cost goal of the competition. This latter effect provides an additional incentive to reduce the target goal still further.

5.2 Value Allocation Review Technique (VART)

5.2.1 Background - Value engineering may be viewed as divided into two application phases:

a. Proposal Phase, and

b. Contract Performance Phase.

The objective of value engineering in the proposal phase is to avoid unnecessary costs by means of a detailed examination and allocation of proposed program costs (See figure 6 (a)). In the contract performance phase, the objective is to implement

the costs developed in the proposal phase, then to determine, periodically, if the amount of the costs should be continued, reallocated, or reduced (See Figure 5 (b)).

In our free economic system, the optimization of value with respect to resource cost may be viewed as a game of strategy involving the buyer and the competitive sellers, several basic assumptions being connected with the proposal and contract performance phases as follows:

a. Proposal Phase - It is assumed that the competing sellers will spend the full amount of contract (at least). This assumption forces the attention of the buyer to ensure that the bid of the winning seller contains no unnecessary cost. Further, the bid by the winning seller must be controlled to the budgeted amount.

b. Contract Performance Phase - It is assumed that the seller will try to increase the scope of the contract, i.e., to cover an underbid, obtain return from cost reduction, and the like. It is also assumed that the pressure from the buyer may force the seller to fulfillment of the proposed design, even if superior alternatives have been developed (a natural aspect of risk).

5.2.2 <u>Technical Discussion</u> - The value allocation review technique involves four fundamental steps in its general application form. These steps are:

a. Step 1 - Allocation of value/cost goals to the procurement of items by the procuring agency.

b. Step 2 - Allocation of value/cost goals to deliverable items by the competitive contractor.

c. Step 3 - Allocation of value/cost goals to item elements by the competitive contractor.

d. Step 4 - Review of value/cost performance by the contractor.

5.2.2.1 <u>Step 1 - Procuring Agency Allocation</u> - The buyer and his associated engineering staff are, in most cases, in the best position to obtain a value/cost goal. This goal should be part of the work statement provided to the sellers. The goal is established using experience data applicable to the item(s) being procured:

PROPOSAL PHASE

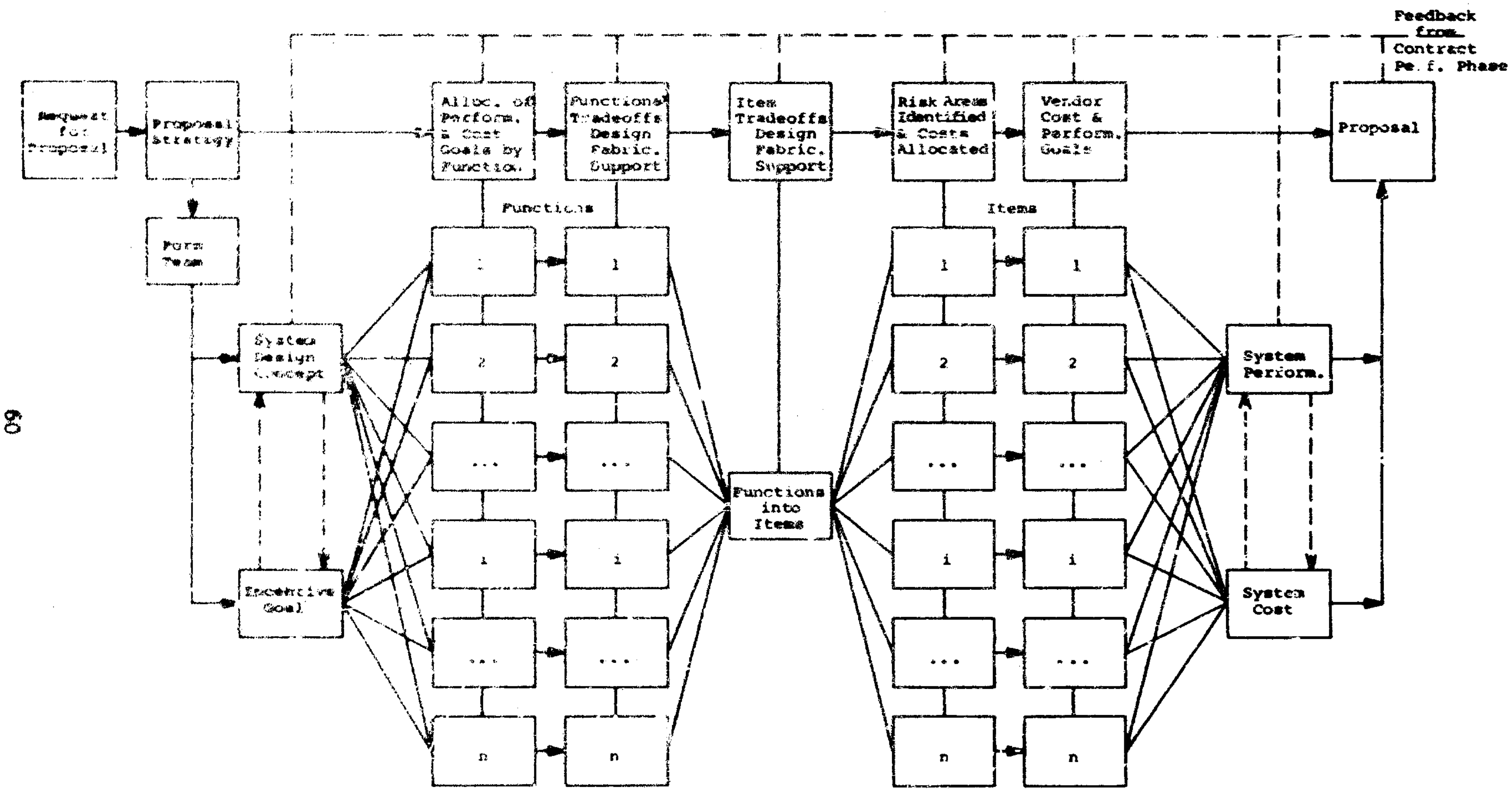

FIGURE 6 (a) VALUE ALLOCATION REVIEW TECHNIQUE

2

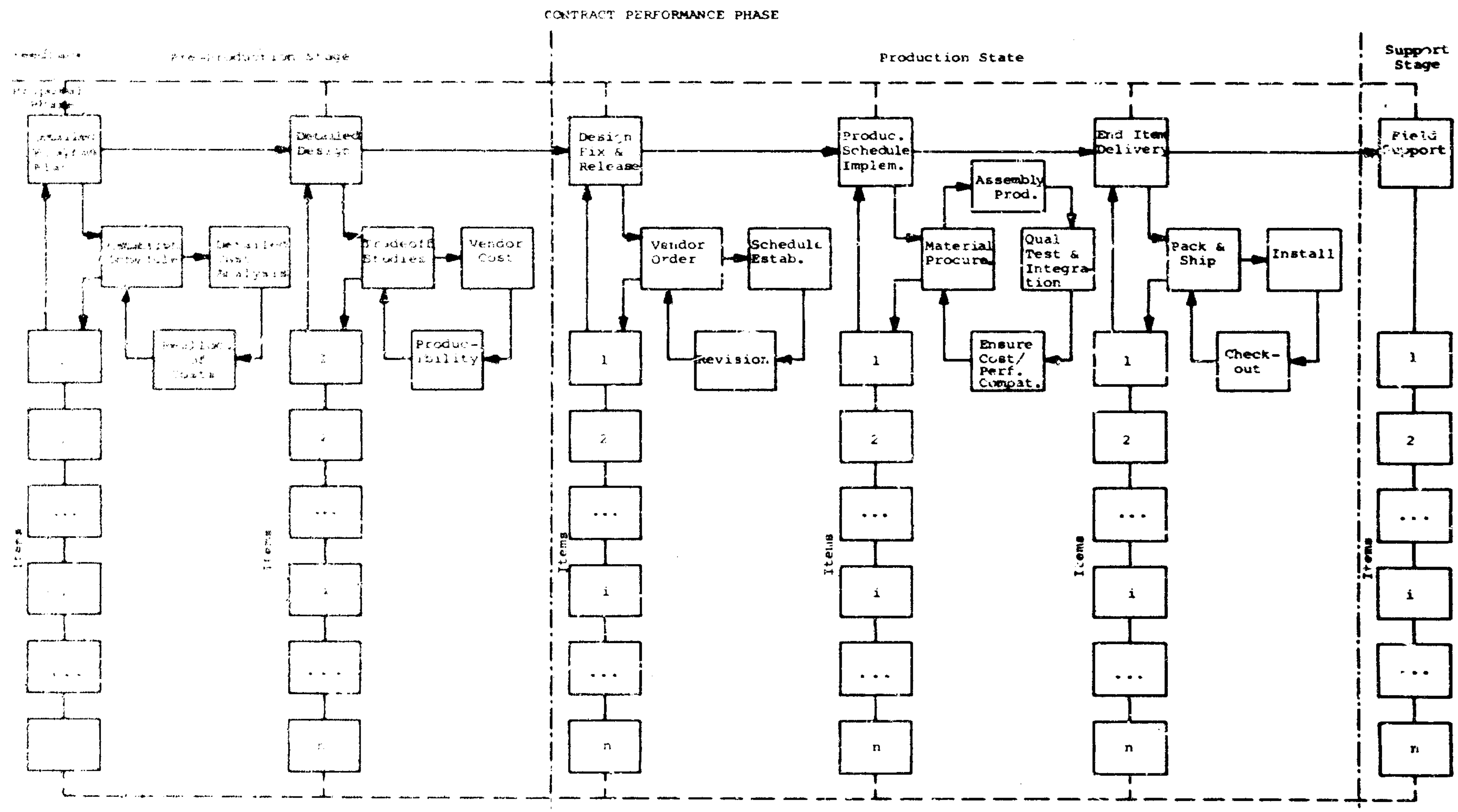

FIGURE 6 (b) VALUE ALLOCATION REVIEW TECHNIQUE

1

2

In general, the cost goal used would be that of the most similar and recent acquisition by the Government, procured in a competitive environment. The cost goal would depend on the number of items of a type being procured. A first step in implementing these buyer's goals would be the development of a value/cost similarity library. These goals should be indexed to permit determination of:

a. Previous procurements which are identical to the current item.

b. Items having the same value, but not the same detailed specifications.

c. Items having both different value and/or detailed specifications.

This value/cost similarity library would ultimately provide correlation for value/cost/time targeting for procurement agencies.

5.2.2.2 <u>Step 2</u> - <u>Contractor Value/Cost Goal Allocation</u> - The competitive contractor will have at his disposal, or should have in order to remain competitive, the following procurement cost goal information:

a. The amount of funds that the procuring agency has allocated for the items (if available).

b. Value/cost goal established in step 1.

c. Appraisal of competitors based on cost of similar items.

d. Self-appraisal, based on in-house technical capability. This cost goal, at most, should be the least of the anticipated costs in a, b, c, or d, above.

5.2.2.3 <u>Step 3</u> - <u>Value/Cost Goal Allocation to Item Elements</u> - Value/cost goals are prorated to item elements, based on their contributions to item cost. These goals are established as follows:

a. From Step 2, the total of the item value/cost goal (T) is established.

b. The allocated value/cost of an item element is established from

$$T_i = kC_i \tag{48}$$

and

$$T = T_1 + T_2 + \ldots + T_i + \ldots T_n$$

where

T_i = allocated cost goal of the item/task,

C_i = experienced cost of a similar item/task,

and k is established from $k = T/\sum_i C_i$

5.2.2.4 Step 4 - Review - The allocated value/cost goals are reviewed at pre-determined monitor points on an item basis. Tradeoffs and/or reallocation of value/cost goals between equipment packages are performed where required. At all times the value/cost goal is reviewed with respect to total expected recurring and non-recurring costs.

5.2.2.5 Value Allocation Review Technique Engineering Team - There are three fundamental areas of tradeoff open to a potential contractor in a competitive bidding situation. The areas involve both recurring and non-recurring costs:

a. Engineering costs

b. Fabrication costs

c. Support and operation costs

Ensuring that the total cost picture is being evaluated and reviewed will require at all points in the program the coordination of the disciplines of design, production, and procurement. These activities, related on an item basis, constitute the functions of the value allocation review technique team, as illustrated in figure 7.

A fundamental practical problem exists in making the design engineers value/cost-conscious. Many techniques, such as Zero Defects programs, cost reduction, incentive pay, and the like, have been used to this end in the past with varying

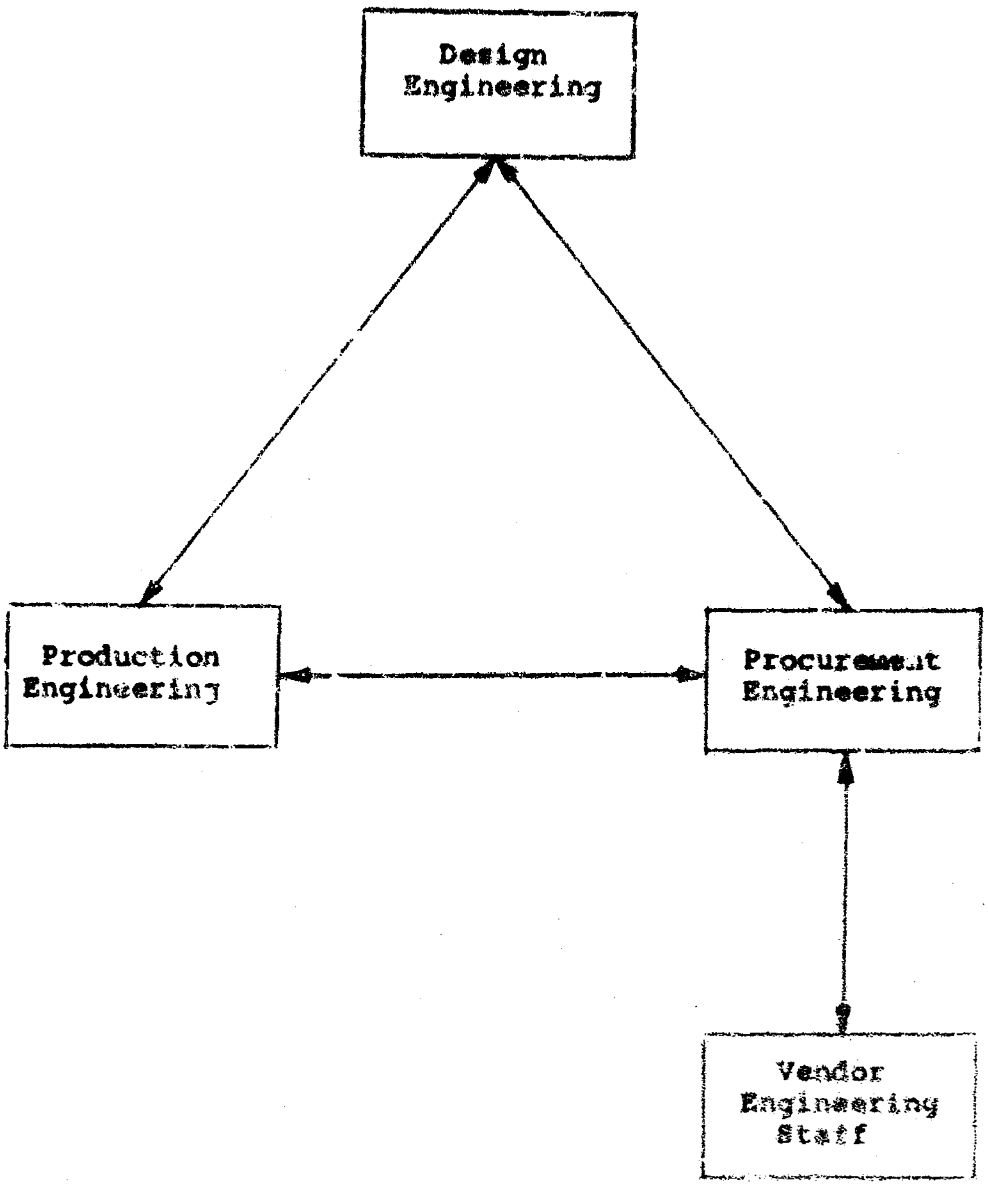

FIGURE 7. VALUE ALLOCATION REVIEW TECHNIQUE TEAM

degrees of success, but all lacking in consistency. The major difficulty in value achievement at least cost lies in the designer's lack of knowledge of manufacturing and support cost. Thus, whereas the designer may quite adequately estimate the cost in terms of labor hours for his effort to produce a design to meet requirements, he is most frequently at a complete loss to estimate the cost implications of manufacture. Conversely, the production engineer is in the same situation with respect to design costs. It is only through coordination of the engineering disciplines that necessary cost consciousness can be achieved.

5.2.2.6 Contractor Application - Value allocation review technique may be considered as an iterative procedure involving the following routine:

a. Establish the system value/cost goal.

b. Allocate value/cost goals to items comprising the system.

c. Perform tradeoffs to achieve value/cost goals.

d. Analyze variation from value/cost goals at item levels.

e. Reallocate value/cost variance funds among items, to ensure achieving the system value/cost goals.

f. Test the sensitivity of the initial value cost system goal by systematically reducing the cost goal in (a), and repeating steps (b) through (e), until the value goal is unachievable.

g. Develop bid cost.

h. Repeat steps (c) through (e) at each scheduled monitor point at the item level.

5.2.2.7 Analysis of Cost Variance - The total cost of a system (T) is identified as follows:

$$T=A+S, \tag{49}$$

where

A = cost of acquisition, and

S = cost of support/operation.

Looking at the dynamic situation, it can be said that

$$\Delta T = \Delta A + \Delta S. \tag{50}$$

Recurring costs related to non-recurring costs - The recurring and non-recurring costs are identified and related to costs of acquisition and support as follows:

$$T = A_n + A_r + S_n + S_r \tag{51}$$

where

A_n = non-recurring costs of acquisition,

A_r = recurring costs of acquisition,

S_n = non-recurring costs of support,

S_r = recurring costs of support,

and

$A_n = \sum_i c_{i-na}$

$A_r = \sum_i c_{i-ra}$

$S_n = \sum_i c_{i-ns}$ and

$S_r = \sum_i c_{i-rs}$

where

c_{i-na} = non-recurring costs of acquisition of item (i),

c_{i-ra} = recurring cost of acquisition of item (i),

c_{i-ns} = non-recurring cost of support of item (i), and

c_{i-rs} = recurring cost of support of item (i).

Let Δc, with the appropriate subscripts, designate a change in the costs as a result of the following:

a. Tradeoff between design and fabrication.

b. Design alternative selection.

c. Design/support alternative selection.

The expression for change in total cost of an item (i) becomes

$$\Delta c_{i-t} = \Delta c_{i-na} + \Delta c_{i-ra} + \Delta c_{i-ns} + \Delta c_{i-rs} . \qquad (52)$$

To obtain the break-even cost, let

$$\Delta c_{i-t} = 0,$$

rearrange the terms

$$(\Delta c_{i-na} + \Delta c_{i-ns}) + (\Delta c_{i-ra} + \Delta c_{i-rs}) = 0,$$

and summing results in

$$(\sum_i \Delta c_{i-na} + \sum_i c_{i-ns}) + (\sum c_{i-ra} + \sum_i c_{i-rs}) = 0$$

The above expression means that for every increase in non-recurring cost, there must be an equivalent decrease in recurring cost, in order not to change the total cost.

<u>Cost estimate-to-go related to cost expended</u> - At any point in the program development, cost control is concerned with two estimates:

a. Estimate-to-go (c_{i-g}) , and

b. Amount expended (c_{i-e}) .

The allocated value/cost to the item/task package (i) should satisfy the condition

$$c_i \geq c_{i-s} + c_{i-e}$$

and $$T = \sum_i c_i - \sum c_{i-s} - \sum c_{i-e} \qquad (53)$$

and using the equations developed previously

$$T = A_{ns} + A_{ne} + A_{rs} + A_{re} + S_{ns} + S_{ne} + S_{rs} + S_{re} \qquad (54)$$

and

$$(T+\Delta T) = (A_{ns} + \Delta A_{ns}) + (A_{ne} + \Delta A_{ne}) + \ldots + (S_{re} + \Delta S_{re}) \qquad (55)$$

where

A_{ns} =Acquisition, non-recurring cost-to-go.

⋮

S_{re} =Support, recurring, amount expended.

<u>Proposal phase</u> - The proposal evaluation toward the value goal is made on an estimate-to-go basis as follows:

$$T = A_{ns} + A_{rs} + S_{ns} + S_{rs} \qquad (56)$$

If $$T \geq A_{ns} + A_{rs} + S_{ns} + S_{rs} \qquad (57)$$

Submit the goal to sensitivity analysis, and if

$$T < A_{ns} + A_{rs} + S_{ns} + S_{rs} \qquad (58)$$

tradeoffs must be performed to achieve the cost goal. If the goal cannot be achieved, the feasibility of the bid must be evaluated.

<u>Contract performance phase</u> - At each succeeding cost monitor point in the program, expenditures and estimates-to-go must be established for each item/task. By task/package, these estimates are summed and compared with the target cost goal for that task package. Where the cost-to-go is exceeded, tradeoffs are required between non-recurring and recurring cost, to meet the target cost goal for that task. Where tradeoffs fail to achieve the cost target goal, variance funds from other task/packages are reallocated to ensure that the overall target cost goal will be met.

The basic criteria for selection of candidates* for value improvement are essentially the same as those used in establishing the value/cost goal allocation. These criteria are:

a. Similarity of item/task to previous value/cost performance records.

b. Identifiable risk involved in achieving the value/cost allocated goal

c. Difference from the allocated value/cost goal.

It should be noted that criteria (a) and (b) are in fact components of the value/cost goal allocation which may be established by the buyer or seller. Thus, the key to selection of potential value/cost improvement rests in the analysis of the differences from the value/cost goal allocation.

From the defined objective statement, the rate of return per unit resource cost can be established. The cost difference for the value/cost goal allocation are given as follows:

$$\Delta c_{i-t} = \Delta_{i-na} + \Delta c_{i-ra} + \Delta c_{i-ns} + \Delta c_{i-rs} . \qquad (59)$$

This expression may be either positive or negative. Where a positive difference exists, the item/task (i) becomes a target for value/cost improvement. If these item/tasks are ranked by order of positive cost difference, item/task preference listings are obtained. If constraints exist, the resources must be expended in such a way that the constraints are not violated.

At any point in the program, cost variance is obtained from the monitored expression for the equipment/task package (i), i.e.,

$$\Delta c_i = \Delta A_{i-na} + \Delta A_{i-ns} + \Delta A_{i-ra} + \Delta A_{i-rs}$$
$$+ \Delta S_{i-na} + \Delta S_{i-ns} + \Delta S_{i-ra} + \Delta S_{i-rs} . \qquad (60)$$

*See Appendix I for additional notes on the selective application of value analysis.

Figure 8 illustrates the tabular format for reviewing, evaluation, and reallocation of project funds.

Figure 9 illustrates a charting technique for monitoring cost with respect to the system target goal. Variation about the system cost goal can be anticipated as the program progresses, but convergence to a system cost below the target goal can be anticipated. For purposes of comparison, the progress of a typical program with value analysis, as it has been practiced, is shown in a dashed line.

5.3 Selective Application of Value Engineering

5.3.1 General - Typically, engineering results are constrained by several specific resource costs. These are as follows:

a. Time - Measured in terms of a scheduled delivery of an item/task.

b. Money - Measured in terms of dollars remaining to complete the program on schedule.

c. Skill - Measured in terms of personnel availability and associated capability to perform tasks remaining on the program schedule.

These constraints are not independent and are, in fact, continuously traded-off in a dynamic research, development, and production program.

5.3.2 Objective - A basic objective of value analysis is to marshall the available resources, which are time, money, and skill, and to direct these resources in achieving a maximum return rate in value per unit resource cost invested. This objective is beset with the problem of dimensionality, in that resource costs involve days, dollars, and people. As a necessity, these resources must be traded continuously, and this trading will depend upon the specific program requirements.

5.3.3 Criteria for selective application of value analysis - The fundamental consideration of value return per unit resource cost should, in all instances, be directed to total expected cost, i.e., recurring and non-recurring costs for engineering, production, and support/operation.

Equipment Package	A_{ns}	ΔA_{ns}	A_{ne}	ΔA_{ne}	A_{rs}	ΔA_{rs}	A_{re}	ΔA_{re}	ΔS_{ns}	ΔS_{ne}	ΔS_{rs}	ΔS_{re}
Totals												
Programmed												
Δ												
Net												

FIGURE 8. COST MONITORING TABULAR FORM

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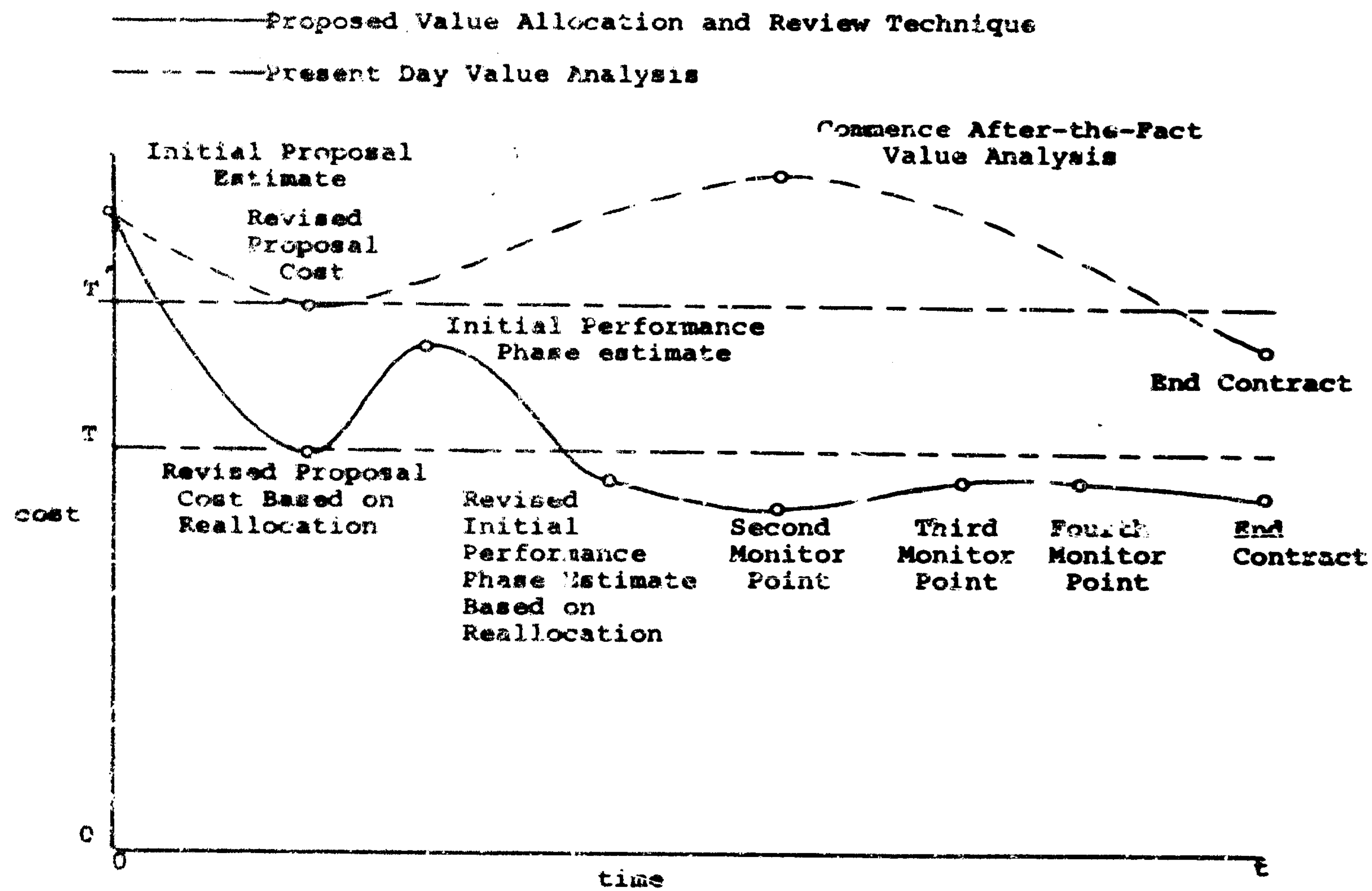

FIGURE 9. TYPICAL COST PROFILE

The cost variance of the equipment/task package (i) is the algebraic sum of the cost differences.

5.3.4 Total expected cost variation analysis - The technique developed above is based on analysis of the variation in total expected cost. Two general constraints are involved, system value parameters (it is assumed that all feasible alternatives satisfy), and acquisition cost goal. Because this cost goal acts as a constraint, the question arises: How is it possible to achieve a minimum total expected cost? A further complication is that the technique does not require establishment of total expected support costs.

The rationale which permits these problems to be avoided is: The allocated value/cost goal on the initial iteration acts as a constraint, that is to say, alternatives which satisfy the acquisition value/cost goal are systematically evaluated to establish a least support cost , based on support cost differences between alternatives. Secondly, the value/cost goal should be varied. This permits evaluation of these questions:

(1) Will an increased acquisition cost produce an offsetting support cost difference to justify the increased expenditure?

(2) Will a decreased acquisition cost be offset by an increased support cost?

If the answer is "yes" to either of these questions, the initial value/cost goal is near optimum. If the answer is negative, alternate proposals should be submitted.

5.3.5 Summary - The value allocation review technique constitutes complete revision of the existing approach to value analysis. Excessive costs must be initially avoided at the proposal phase to achieve value optimization. The approach is direct, in that it recognizes the competitive environment in which the buyer and sellers exist, and is directed to the causes involved in the generation of excessive cost (lack of control). Cost accountability, being established on an item/task total cost basis, forces cost consciousness upon the design, fabrication, and procurement functions as a team, and permits tradeoffs to be made with excessive cost areas.

Although emphasis has been placed on the Government participation in establishment of cost goals, and upon a competitive environment, the technique is equally applicable to situations which do not contain these elements.

The value allocation review technique is directed to the achivement of:

a. Compatibility with the competitive environment, with the net effect of sharpening competition while narrowing the field of competitors.

b. Compatibility with standard activity network analysis increases the overall timeliness of achieving accurate cost performance estimates.

c. The technique enhances contractor operations as follows:

(1) Requires essentially no additional management effort.

(2) Permits self-appraisal by potential bidder.

(3) Permits establishment of cost control mechanism and control levels for subsequent program phases.

(4) Provides criteria for directing and selecting vendor products and cost goals.

(5) Lessens the tendency towards redundant costs in a proposal.

d. The technique also creates value/cost awareness, as it

(1) Forces cost awareness and accountability on design/manufacturing engineering.

(2) Forces tradeoff among engineering, manufacturing, and support cost (tradeoff between non-recurring and recurring costs).

6. THE DECISION ENVIRONMENT

6.1 General

This section presents the fundamental concepts, the working definitions for the value methodology, and the program time frame in which value analysis must be performed. For the purpose of this study, value engineering is considered to be that discipline concerned with analysis of how system and equipment are related, whereas system engineering is directed to analysis of the relationship between the mission of the system. Thus, as the systems effectiveness analyst is related to the system engineer, so is the value analyst related to the design engineer. Pictorially, this relationship is shown in figure 10.

The elements common between system effectiveness and system value are the hardware/software to implement the system and the related support aspects. Additionally, the interface of systems effectiveness and system value revolves about the method of implementing the function. In general, this will involve hardware, but may relate to processes, schedules, and the like-anything concerned with program schedule, total expected cost, or performance.

6.1.1 Definitions - Like any other prediction/measurement tool, value engineering can be predicated on an axiomatic set of assumptions, describing as realistically as possible the ground rules of the discipline. Value, for the present purpose, is appropriately viewed as the utility of a proposed system - equipment to the user, measured in terms of monetary value of an achieved objective. (Reference equation 2, page 9, section 2.2.2). Where the objective and its value are specified and fixed, the relative value of an alternative system can be described in terms of its capability for achievement of the objective. For military systems, this capability is quantifiable in terms of performance measures of the system's utility for its anticipated mission profile.

The term "objective" may be considered synonymous with the term "function" as used in value engineering literature.

Value engineering analysis is a quantitative and systematic method directed to the achivement of specified performance objectives equal to or greater than some pre-assigned value at minimum resource expenditure. The term "system" is used in this report as an achievable objective specified in terms of performance parameters, which are transformable into hardware, and/or processes, and/or schedules.

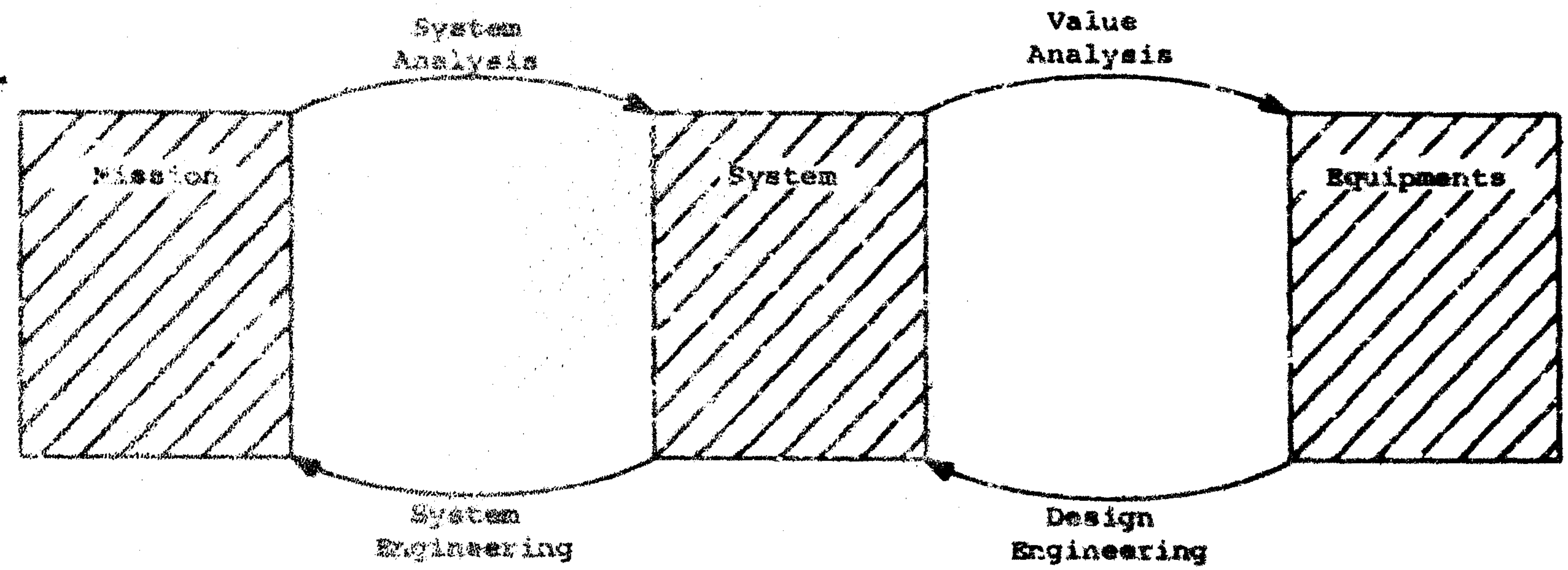

Figure 10. System Disciplines

2

6.1.1.1 System value parameters - In general, there are two types of system value parameters. These are shown in table 7. The basic value parameters are:

a. Design value parameters - These parameters establish the design requirements imposed on the system. The capability parameter is defined in terms of mission requirements. Each proposed design alternative may be predicted with respect to satisfying the parameter numeric. Generally this would be accomplished using modeling techniques. Demonstration testing may be conducted to ensure satisfaction of the parameter numeric, with the exception of the survivability and safety parameters, for which it may not be feasible.

b. Operational value parameters - These parameters describe the use value of the system.

The design and use value parameters constitute the total value to the Government. Specific numerical description of each design and use value parameter is to be provided by the Government.

Value parameters, as previously defined, satisfy quantitative requirements, prediction, and demonstration requirements, and, as importantly, they represent utility of the system to the Government in terms of achieving an objective(s).

6.1.1.2 System utilization rates - The value of the system is related to the cost of the system through utilization rates (See table 5). The prime utilization rate is the operational rate, viz., how much is something used. All other rates are either part of the operational rate (training rate) or derivatives of it (maintenance rates).

6.1.1.3 Dependent variables - The system utilization rates, operating on design and operation value parameters, combine to determine both acquisition and support cost. Thus, for a well defined system design configuration (design and operational value parameters specified along with hardware implementation), the total expected cost of acquisition and support may be estimated, using the system utilization rates. The system utilization rates are intimately related to how the system value objective is achieved, namely, hardware alternatives. These alternatives are, in turn, related to basic cost inputs of acquisition and support.

TABLE 7
PARAMETER DEFINITION

System Value Parameters	System Utilization Rates	Acquisition Cost (Dependent Variable)	Support Cost (Dependent Variable)
Design			
Capability			
Availability			
Reliability		Design	Personnel Subsystems
Maintainability			Manning Requirements
Survivability		Fabrication	Skill Requirements
Safety			by location
		Installation	
	Scheduled Rates	Manuals	Spares
	Scheduled		by type
	Unscheduled	Test Equipment	by location
	Spares usage rates		Utilities
	Training rates	Tool	by location
	Operational rates		Facilities
		Fixtures	by location
Operational			Depot costs
Deployment Capability			Transportation
Self-sufficiency			by location
Mobility			Installation
Storeability			by location
Life Expectancy			Documentation

2

1

6.1.2 Information Adequacy - At any point in the system development cycle, the information upon which decisions are based is in the form of estimates. Greater detail and accuracy may be obtained, but only at the expense of time and cost and, perhaps, national safety. To assure optimality, information accuracy sufficient to ensure that one alternative is superior to another is all that is required.

From the definition of value, and its relation to total expected cost, it is apparent that system value can be predicted only with the same degree of accuracy as the basic value parameters. Recognizing that real difference in total expected cost is the principal criterion, information sufficient to ensure that one alternative is superior to another is also sufficient to assure that the minimum cost goal can be achieved. This particular feature is singularly significant, in that as the hardware configuration becomes more defined, variations in cost estimations for acquisition and support decrease. Further, for the purposes of comparing alternatives, the points of differences between alternatives may be singled out and, if necessary, greater detail information acquired.

In general, acquisition costs are best provided by the contractor, since this is the source of alternatives and basic cost inputs. In order to project operation and support cost as a function of design alternatives, the USAF must be the source of operational parameters and specified cost constants. The system utilization rates will be a joint responsibility. The utilization rates are a primary target for sensitivity analysis.

The prospective contractor must compare alternatives and perform tradeoffs to assure proposing the least cost configuration meeting value requirements from the alternatives available to him. Evaluation of each proposed configuration in comparison with those of different prospective contractors is feasible only by the Government.

It is necessary from both the viewpoints of Government and the contractor that a common method of analysis be used for comparison of alternatives by the contractor and by the Government. This is encouraged by the Government in advising that proposals will be evaluated by the technique described in this report, and recommending that prospective contractors use the same method to evaluate their alternatives. Further encouragement is provided with the requirement that the contractor provide value and cost data in format required by the Government for comparison purposes. The prospective contractor will be

required to provide estimated acquisition costs and support parameter values, to serve as bases for support cost difference between alternatives of different contractors. The resulting contract will incorporate as requirements those cost and performance parameters upon which the decision was based.

6.1.3 Value Analysis in the Continuous Time Domain - The basic requirements of the mathematical model or analysis technique are that it be capable of application in the time frame in which the problem exists and, additionally, that it be capable of utilizing information of limited accuracy. The refinement (closeness of fit) of the model should be predicated upon exactness of the information processed.

Throughout the conceptual phases of system development, decisions are made sequentially with increasingly more accurate estimates of system performance and cost. In spite of the relatively inaccurate information available in the earlier stages, decisions still must be made concerning alternatives, and to ensure that the proper alternative is selected, the methodology of processing available information must permit finding quantitative differences between alternatives.

Figure 11(a) depicts the broad cause-and-effect relationships that in actual practice develop into a chain of events that terminates in a deployed and operational system. The important features are:

a. As time progresses, the alternatives available for subsequent phases become increasingly constrained.

b. Changes in concept at any phase can be reflected in terms of resource cost in subsequent phases.

c. Input (requirements) at any phase may be categorically related to previous decisions, or shown to be relatively independent.

Figure 11(b) depicts the same phases with feedback provision. This feedback is simulated in that alternatives at any phase are extrapolated into the terminal phases of the system life cycle. The value advantages afforded by simulated feedback are:

a. It minimizes constraining requirements on subsequent phases without tested, long-range effects.

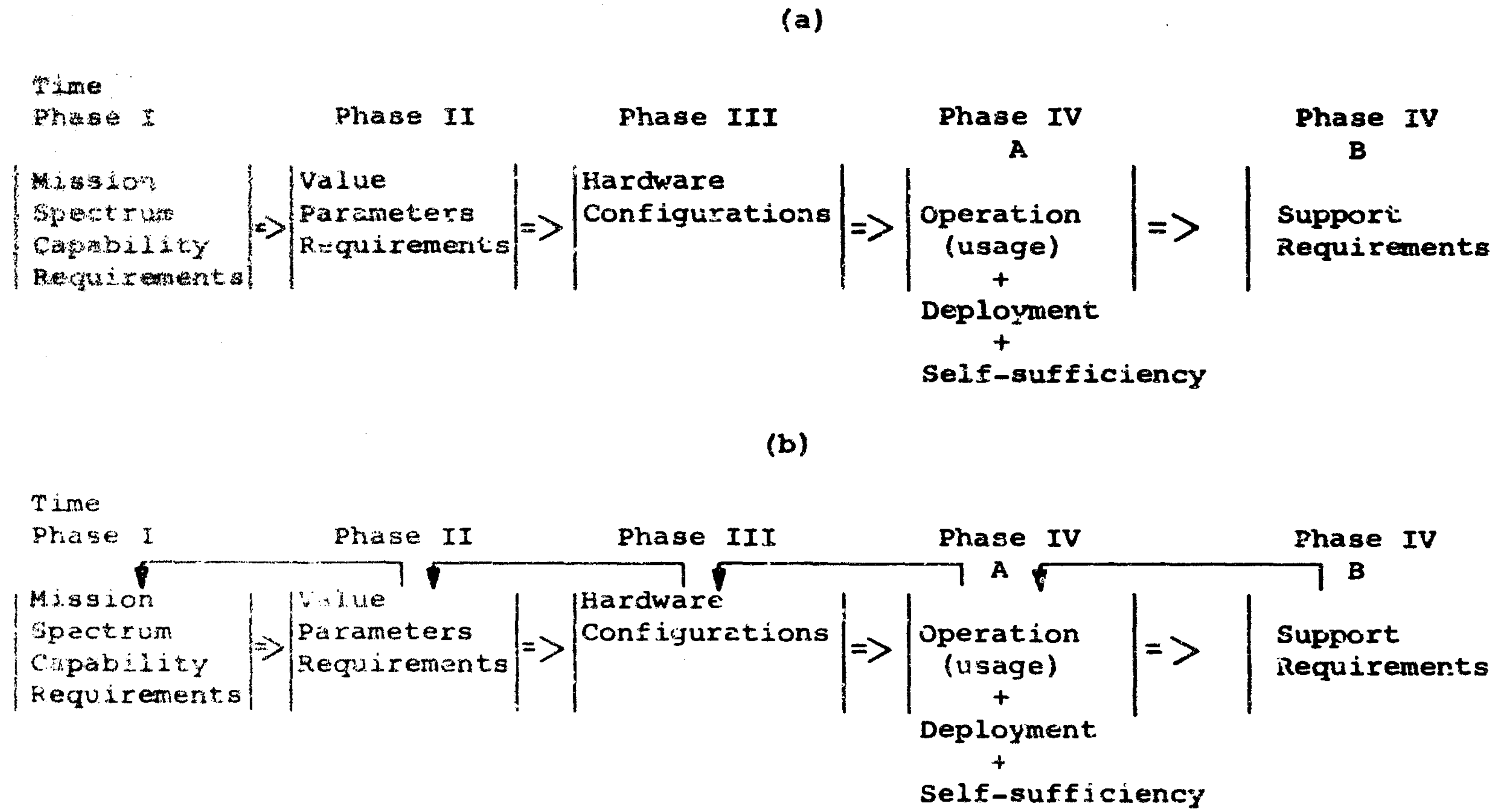

Figure 11. System Development

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b. It permits relative evaluation of alternatives

c. It permits sensitivity analysis to be performed. This type of analysis takes the following forms:

1. Determination of importance to non-importance of a decision.
2. Determination of effect, if a change is necessitated in a subsequent phase of life cycle.
3. Pointup of areas of high cost sensitivity.

Figure 12 provides a detailed picture of the system program phasing. Opportunity for change exists at every phase and at every level of system development.

Many alternatives will involve relatively simple decisions, whereas others may be more complex. The simpler evaluations will generally involve only acquisition cost, there being no essential difference in value parameters, or alternately, only difference in support cost. Another aspect which characterizes these simpler evaluations will be the independence of subsequent decisions involving the system. However, in general, particularly of the more important decisions, the sequential aspect of the decisions will predominate. The question quite naturally arises of the feasibility of being able to completely define a particular configuration during a preceding system conceptual phase. The practical aspects of this question are available time, cost, and information adequacy. It should be recognized that as the hardware becomes more defined, decisions involving changes or modifications become relatively less important than the decisions made at a previous stage. Further, only sufficient information is required to ensure that the best of the feasible alternatives are selected, thus, information is required only sufficient to ensure dominance of one alternative over another.

6.1.4 Method of Application - It is important to recognize that equations are not likely to be developed which extrapolate design value parameters in conjunction with operational value parameters into exact support costs. However, from the viewpoint of value analysis, it is not necessary to have such comprehensive equations. What is necessary is the ability to evaluate alternatives via cost/performance differences.

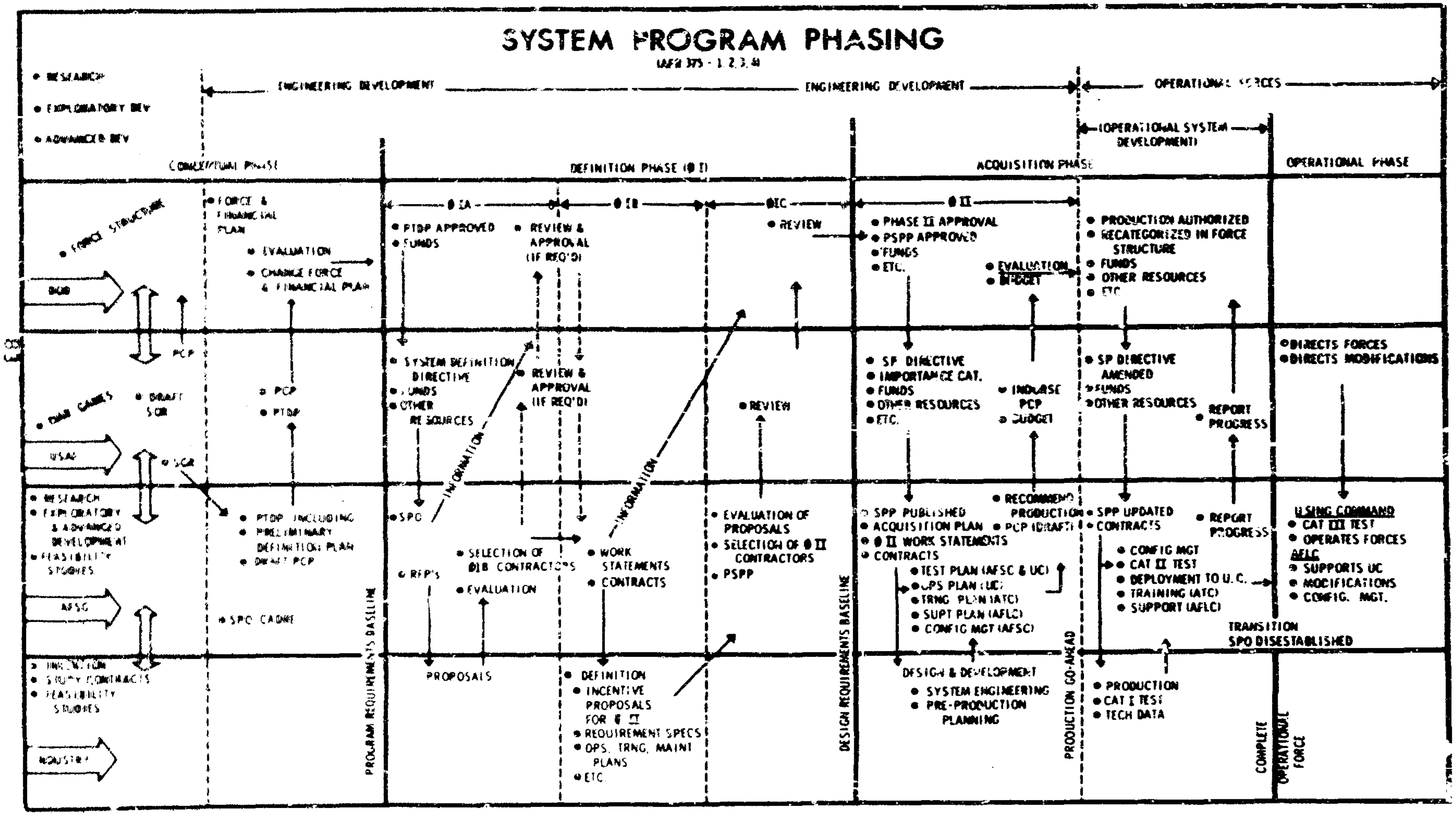


Figure 12. System Program Phasing

2

The cost methodology aspect of value analysis is of primary significance, since any required sophistication and/or information and documentation may offset advantages offered by the technique.

The primary advantage of the proposed approach is that it permits individual contractors to use their own cost accounting systems. The only requirement is the ability to differentiate between alternatives as measured by acquisition and support cost.

6.2 Value and Cost Analysis

The method of analysis is based on the sequential decision processes, characterized by a logical sequence of events. The events are of three types:

a. Feasible alternatives.

b. Chance events.

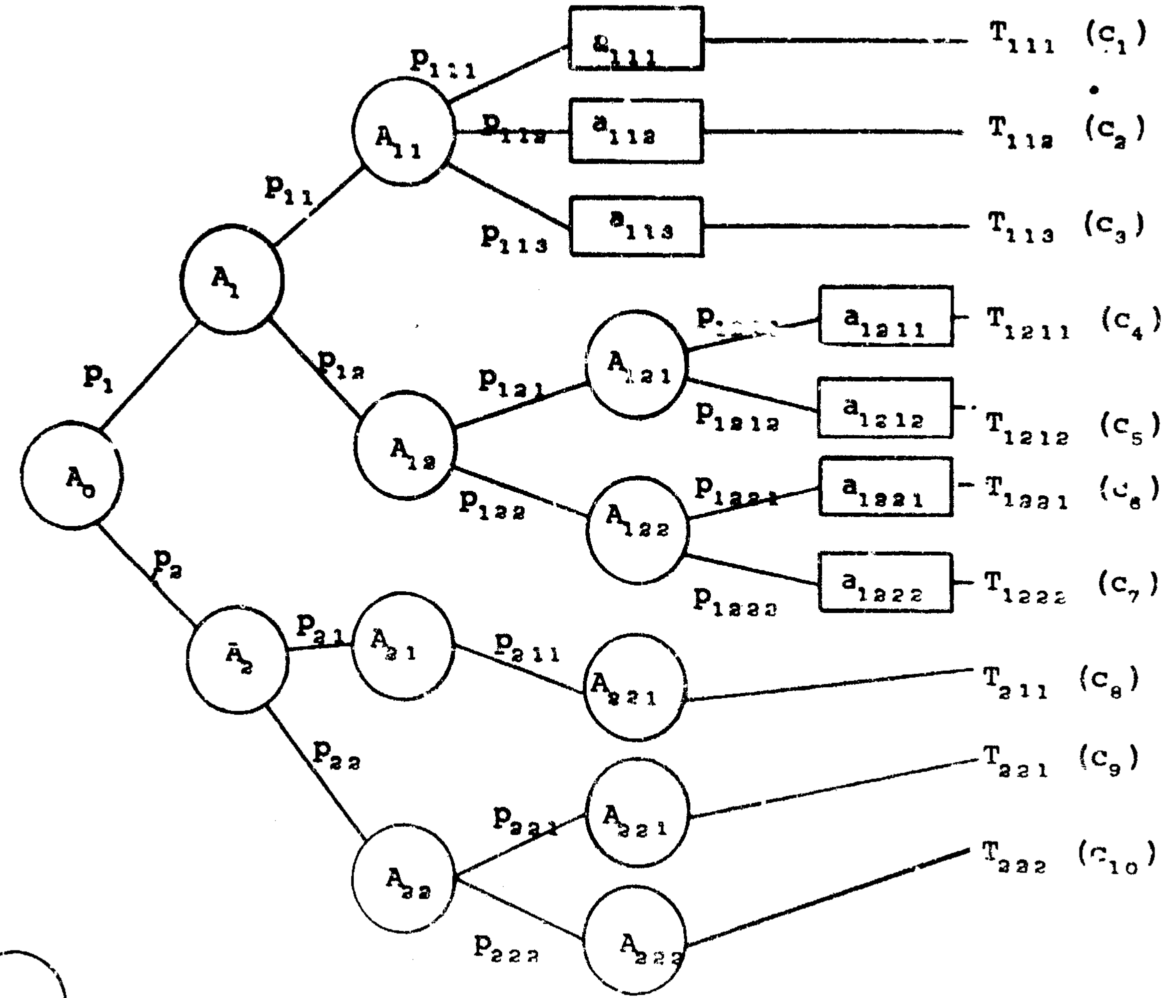
c. Program schedule.

The approach is commonly treated in literature as a decision tree.

This sequential decision approach is analogous to dynamic programming, in that alternatives which possess both contingency events and subalternatives are evaluated, using a backward evaluation process. This feature permits significant computational reduction, which otherwise could render the technique infeasible.

Each sequence in the decision tree may be considered a strategy. Associated with each strategy is a resource cost. The optimum resource cost is found by successively evaluating each alternative in the backward sense. At each common branch point, rolling backward, the most costly alternative is eliminated.

6.2.1 The Decision Tree - The technique to be employed is most easily grasped using the decision tree diagram. This is shown in figure 13. The circled (o) entries represent feasible alternatives and the boxed $\boxed{}$ entries represent chance events. Associated with each chance event is an estimated probability of occurrence (P_{ijk}...). Regardless of the specific sequence chosen, each sequence results in a terminal event



A_{ijk}... = a feasible alternative

a_{ijk}... = a chance event

p_{ijk}... = a probability of occurrence of the following alternative or event.

T_{ijk}... = a terminal event

c_i = the cost of alternative A_0, A_i, A_{ij}, A_{ijk}, ..., represented by T_{ijk}...

Figure 13 The Decision Tree

(T_{ijk}...) which, in this case, represents a complete definition of a proposed configuration of the system, complete with the cost (c) of the alternative. The sequential decision tree may be considered the sequence of increasing definition of the system design, the branches representing alternate approaches at successively greater levels of system definition.

6.2.2 Evaluation of Alternates - The first step in the evaluation process is the establishment of feasibility. Specifically, two types of constraints must be met. These are, from the value function of paragraph 2.2.5:

a. $t_i \leq t_o$

t_i = time required to implement the strategy.

t_o = allowable time limit.

b. $E \leq E_o$

E = value of effectiveness function.

E_o = minimum required value of effectiveness function.

Here (t_i) may be established using an activity network technique and (E) is established using either the standard prediction techniques (reliability, maintainability, etc.) or a prediction model specifically developed for the specific system parameter.

The second step in the process (having eliminated those alternatives which do not satisfy either or both constraints above) is the estimation of the total resource cost. This may be accomplished using the individual contractor cost accounting or activity network techniques. Starting from the terminal points in figure 13, the more costly alternatives are eliminated. Note that an alternative is costed from the terminal point to the highest level of assembly (to A_o, if necessary) at which the decision has a significant cost implication. This procedure is reiterated until only one alternative remains. The degree of accuracy involved in the costing analysis should be guided, as necessary, to demonstrate that one alternative is superior to the other.

As an example (Figure 13), consider alternatives A_{321} and A_{322}, defined as the decision to repair or discard at the module level of assembly in the event of failure. No design implications are involved in the decision. The cost difference is in

costs for spares, personnel, etc., for repair or replacement of modules. In this example, no additional cost difference is reflected into the higher assembly level (A_{e2}), or higher, and therefore only the cost difference at module level need be considered for the decision. Other alternatives may require consideration of cost differences at multiple levels of assembly.

6.2.3 Concept of Cost Analysis, Inputed Cost, and Risk Cost Analysis - All value analysis problems are ultimately reducible to the following simple balancing problem:

Let (c_a) designate the cost of analysis,

(c_i) designate the cost to implement the recommended alternatives, and

(c_s) designate the anticipated total expected cost differential.

The, ($c_a+c_i<c_s$), if value analysis is to be a paying proposition.

Imputed cost - Let (p) designate the probability that the system will perform, as designed, over the expected life of the system.

Let (Δp) designate an incremental increase in the performance of the system as a result of acceptance of a design/support alternative, and let (Δc) designate the incremental cost of implementing the design/support alternative.

The expected return from the investment of the resource cost (c) must be at least

$$v\Delta p = \Delta c \text{ or} \tag{60}$$

$$v \lesseqgtr \frac{\Delta c}{\Delta p} , \tag{61}$$

where (v) now is the imputed resource cost saved if the alternais accepted (incorporated).

Risk - The concept of risk is always associated with a program in some form. These risks will usually fall into the following categories:

Scheduled Completion	(Time)
Technical Feasibility	(Performance)
Budget	(Cost)

Unfortunately, a problem in one area tends to create excesses in another.

Where uncertainty is involved in a particular strategy, the following approach is suggested:

a. Assume that a particular course of action will be taken and evaluate it in relation to alternatives.

b. If the return in cost savings for the risk alternative exceeds other alternatives, the following cases arise:

(1) The expected savings using the cost risk strategy should at least offset the addition of expected cost expenditure if the risk strategy fails.

(2) Additionally, further investment may be made to gain adequate information and reduce or eliminate the risk.

Perhaps the best means of coping with this aspect of a program is an activity network which lays the program out with respect to time sequencing and cost. This approach also permits analysis of the effects of potential errors.

The question of technical feasibility can be handled similarly:

Let (p) designate the probability that a specific element in the technical approach (alternative 1) is feasible, and

Let (q) designate the probability that an acceptable but less desirable approach (alternative 2) is necessary.

The probability that the second approach will be required is

$$q = (1-p).$$

Let a_1 = cost of implementing alternative 1, if feasible,

b_1 = cost of determining feasibility of alternative 1, and

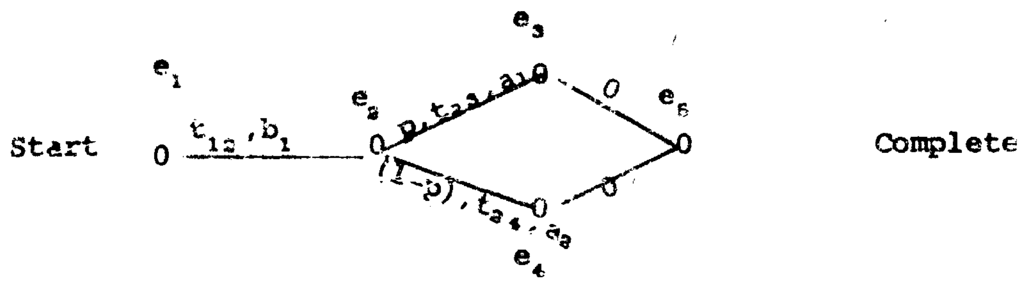
a_2 = cost of implementing alternative 2.

The total expected cost becomes:

$$TEC=a_1p+b_1+a_2(1-p). \quad (62)$$

The break-even point is established by setting TEC=0.

This risk analysis may be subjected to schedule timeliness analysis using an extended concept of an activity network, as shown in the following diagram:



where (e_i) designates an event, and (t_{ij}) designates time from e_i to e_j.

The expected time schedule is given by

$$T=t_{12}+p_1t_{23}+(1-p)t_{24}. \quad (63)$$

Thus, this sub-network may be readily incorporated in a major program activity network.

The concept of total expected cost has broad implication and is an effective medium, when properly exercised. Numerous enigmatic problems, in principle at least, become readily resolved.

Given two alternatives, (a) and (b), suppose alternative (b) is in a position to utilize certain equipment, facilities, etc., which already exist. Suppose also, that were it not for these seeming advantages, alternative (a) would be superior. The question now arises as to whether alternative (b) should be charged the cost initially incurred (or existing worth) of the presently unutilized or underutilized equipment, facilities, etc. Two schools of thought exist on this question:

a. Charges should be invoked on alternative (b) because, subsequently, a demand for the presently unused/ underutilized facilities may be made, which will force a new acquisition.

b. Charges should not be invoked because the investment has already been made, and the facilities, etc., are unused.

In the limiting form, both positions above are valid where certainty is involved, namely, it will be demanded in the future or it will not be demanded in the future. What is clearly required is a look at the expected cost, which includes expected future use of the available facilities, and the like. Accordingly, estimate the likelihood of the facilities being otherwise in demand, and, in fact, cost-analyze the alternatives. Logically, this is structured as follows:

Let c_a = Cost of alternative (a).

c_{bo} = Cost of alternative (b), if unused facilities, etc., are not charged.

Δc_b = incurred incremental cost of alternative (b), if facilities are used and a subsequent demand is made.

p = probability that a demand will be made for unused facilities, etc.

The expected cost of alternative (b) becomes

$$E(c_b)=c_{bo}+p\Delta c_b \tag{64}$$

and

$$\Delta c_{ab}=c_a-E(c_b). \tag{65}$$

Incremental analysis (differences in cost between alternatives) can result in poor decision making, if the concept of differences in total expected cost is violated. Examples of this abound, e.g., change of outside purchase services to in-house services, based on no immediate additional requirements in fixed costs. However, when expansion is required, the previous decision proves to be a poor choice. This comes about due to inadequate planning.

What is required to ensure proper decision making is projection of the feasible alternatives, i.e., the decision tree approach.

adequately treating expected events and predication of the analysis on the sought-after objective (total expected cost, total expected profit, etc). It is standard practice in industry to develop (plan) marketing, markets, on a monthly, quarterly, and annual basis. Generally, five-year plans are developed on an annual basis. This is done to provide adequate short-and-long-range planning information, to permit analysis in terms of differences in total expected profits.

The cost method used herein for general analysis avoids consideration of interest. This position has been taken for the following reasons:

a. Interest is charged on all commodities at the same rate. Thus, individual commodity interest need not be computed.

b. The minimum cost point is unaffected by the application of interest costs.

c. The method of the analysis is restricted to establishment of total expected variable cost, and the goal is the establishment of the best support and acquisition policy.

The interest paid on the funds is not related to how the funds are spent. The value of the funds, as measured by an alternate means of investment, e.g., reduction of national debt, has already been established by the requirement for a system having specified performance requirements.

The cost analysis method developed does not use proration as a device to assign costs, but, instead, is predicated on demonstrable difference in cost as a result of choosing a design/support alternative.

The Federal Budget is largely paid off each year by means of taxes, therefore, not more than one year's interest should be chargeable to system costs. Because of the means of acquisition of the funds, no difference in interest period should be chargeable to capital outlay, or operation and maintenance costs. Thus, if the alternative selection criteria included application of life cycle interest (or anything near it) to capital outlay, greater future federal budgets would be required. The criteria would tend to select systems with lower acquisition costs and higher operation/maintenance costs, which, because of the annual nature of money acquisition, would require larger total expenditures.

7. TECHNIQUE VALIDITY, ACCURACY, AND SOURCES OF ERROR.

Technique Structure: The technique structure rests on cost differences as opposed to prediction of total cost. It is desired that the technique deal with quantifiable variables and demonstrate differences in approaches (alternatives).

This method of cost analysis obviates certain subtleties which would otherwise be encountered if total expected costs were used rather than total expected cost differences;

a. Accounting for shared utilities, facilities, personnel, etc., wherever the difference may arise

b. Specifically, it may be impractical to determine the total expected cost implication of a design alternative.

c. Since only those cost factors are analyzed which possess differences between alternatives, sufficient attention can be applied to the significant factors to minimize the effect of error upon a decision.

Important to this concept is the fact that the cost charged to the Government for an item is its real cost. The fundamental concern relative to the technique structure is whether it permits evaluation of alternatives which possess differences in cost to the government. The validation of these characteristics of the technique structure does not rest on the ability to predict cost, but on ability to predict cost differences with sufficient accuracy to permit decision-making. Consider the following:

Vendor A quotes x dollars to a contractor for an item. Vendor B quotes y to the contractor ($y<x$). The contractor is unconcerned with the internal processes which generate the costs x and y. If the item is to be incorporated as a part of an end product, this difference in cost may be passed on to the Government by the contractor. A real case in point is the TFX decision, which was based on the cost difference implied through commonality of design. It is to be noted that the manufacturers' cost proposals were on a CPFF basis, and could be expected to have considerable potential for variance, but the cost difference implied by the designs was valid.

For a technique, procedure, or mathematical model to be useful, it must provide acceptable levels of validity, reliability, and

economy in application.

The technique developed in the previous sections has two aspects of validity; these are described by the following questions:

a. Does the technique permit valid cost/performance decisions?

b. Does the technique permit valid decision making without making detailed cost comparison between predicted and incurred cost.

The major objective of the technique is cost avoidance. In the contract phase, funds will have been committed and the key to cost avoidance will be through modifications of initially proposed hardware/software/operations/support designs. To ensure cost avoidance, it is mandatory that incentives exist for contractors to make modifications in the initially proposed design.

The proposed value methodology permits individual contractors to submit proposals based on least total expected cost, and provides the U. S. Air Force a means of evaluating the individual contractor proposals relative to each other and thus, of establishing a least total expected cost decision.

The validity of this approach rests on two assumptions:

a. The winning contractor is committed to deliver the end product consistent with contractual constraints.

b. The Government evaluation is performed using the proposed methodology, and the contract is monitored on the basis recommended.

For contractor cost, the model possesses prima facie validity in that decisions are based directly on known or estimated cost differences existing at the time of the decision. The validity of the technique depends upon only the thoroughness of analysis of the technique users. This amounts to seeking out significant differences between alternatives which can affect a decision.

The position taken in this report is that detail cost accuracy can be obtained, but at the expense of program time and funds to sustain the cost investigation in greater detail.

More importantly, it is stressed that cost comparisons of alternatives should be evaluated only to the point that a condition of dominance of one alternative over the other is established. This is patently important to achieve economy of application in both timeliness and funds expended.

Cost predictability falls into two general categories. Some costs can be estimated directly, and the estimates control actual spending. In these cases, the predictions become self-fulfilling. The acceptance of a proposed alternative from the design team by the fabrication and procurement personnel actually constitutes the validity of the cost estimation procedure. The process involved can be considered much the same as buying on the open market.

The manufacturing people are charged with the responsibility of producing hardware at a specified budget which is established on a basis of what is to be done. If a proposed hardware alternative is postulated by design and procurement is to be implementable at a specified cost, this must be demonstrated to manufacturing, or manufacturing will not assume the financial responsibility. Manufacturing cost now becomes largely self-fulfilling. Similary, procurement is part of the check and balance which ensures validity of cost estimates by obtaining cost data/quotes from vendors to ensure that material costs are compatible with design and manufacturing estimates. Other costs must be estimated, using cost projection techniques. These latter costs are subject to error because:

a. Many costs are of a recurring nature, and significant changes in commodity price come about with the passage of time.

b. The method of incurring cost in the support and/or operational phase may not, in fact, agree with the supposed method using cost projection equations.

c. The rate of obsolescence of an item may be influenced by state-of-art improvement; also different deployment schemes may develop, which will affect the operational posture and support structure.

For the case of the recurring support cost prediction, the problem must be squarely faced; a value/cost decision must be made, and selection of the best value/cost alternative is desired. In general, analysis via dominance will usually be required, and this condition is best tested by analysis of error sources relevant

to the particular alternatives being evaluated.

For particular decisions, specific detailed cost models may be required (as an example, see appendix VII), but this feature will not invalidate the general methodology. Where the expected cost error exceeds the difference between alternatives, more refined estimates may be required, depending upon the importance of the decision.

General sources of error are developed and examined in the sections which follow. There are two major characteristics of the proposed difference analysis which provide an intuitive validation of this approach. These are:

a. Where errors are involved in the operational factors, the errors will generally be in the same direction for the alternatives being evaluated, e.g.. failure rate, expected lifetime.

b. The aggregate error within an alternative will be less than the absolute sum of errors because errors will tend to cancel.

Specific Error Sources.

Appendices III and VI on manning and sparing, respectively, have self-contained descriptions of error sources of major influence.

The amount of error introduced into the cost analysis from the various inputs will depend generally upon the characteristics of the specific system under analysis. In general, the relative error output of the cost model will be less than the relative error input. As the worst, the cost error will be linearly related to the error input, and this will occur when there is small variation in the system demand rates.

Manning Analysis.

Manning Cost Error Sources - The major sources of error in manning will be due to errors in failure and maintenance rates. Where self-sufficiency dictates a manning relatively independent of work load, this source of error becomes negligible. Where a significant amount of work is performed at a location, a sensitivity analysis may be performed to establish potential cost error. Refinement in predictions may be made, if significant differences are found.

Secondary manning errors will fall into five categories:

1. Personnel turnover rates.

2. Pay schedules.

3. Skill level assignments.

4. Skill packaging.

5. Assumed independence of subsystems contributing unreadiness.

Turnover rates (see appendix III) dictate pipeline personnel requirements. These rates will be a function of the organization type. To some extent, these rates are controllable (through reenlistment bonus, etc.).

Pay schedules are relatively stable and will constitute only minor differences. Skill level assignment can be a major source of error from two aspects: underestimating skill requirements has the effect of increasing service time, which reflects in unreadiness. Overestimating skill requirements has its main effect in requiring additional pipeline personnel. See appendix III.

Skill packaging constitutes assignment of work responsibility to particular skill types and levels. This is generally accomplished by skill assignments based on equipment or subsystem type. In general, if reasonable primary workloads are maintained this will not constitute a major source of error.

Independent unreadiness contributions are assumed from different subsytems. Methods exist for compensation where the independence assumption does not hold (see AMRL-TDR-64-21, appendices III, IV, and V.). The error would be to overestimate unreadiness. In general, this would not have significant effect upon selection between alternatives.

Depot Labor Costs

For the depot, the labor cost prediction error varies linearly with failure rate or repair time error. The basic cost rates per labor hour can generally be obtained directly from the candidate depot work source. Labor rates will be a function of time over the expected lifetime of the system. The variation of labor rate with time tends to increase the labor rate, but this effect tends to be compensated by other rising costs. This should not be a significant source of error.

Depot Inventory Costs.

Cost Constants - These constants, it is anticipated, will be updated with time, as required.

These constants are based on a large sample and proration of overhead costs. Error in these constants will not cause significant cost analysis errors for the following reasons:

1. Expected error values are small.

2. Errors tend to the same direction for all alternatives.

3. The contribution of constant factors to alternative cost difference is small.

There are several basic parameters upon which the proposed technique is heavily dependent. These are:

a. Expected lifetime of the end item(s) being acquired and supported.

b. Demand for service per unit time.

c. Service time per demand.

d. Permissible unreadiness of end item supported.

The expected system life is one of the more important parameters in the cost analysis. The influence of this parameter manifests itself particularly in:

a. Cost of operating/maintenance personnel,

b. Cost of spares (consumables), and

c. Cost of facilities and utilities

Considering two alternatives, there is natural reluctance to select the alternative offering least cost, if this cost is achieved by reducing support cost. This is due to the uncertainty associated with the expected deployment life. This reluctance comes about as a result of:

a. Trading a reasonably firm cost (negotiated between buyer and seller) against an expected cost of lesser certainty.

b. A natural tendency to suboptimize, that is, where the seller does not have the responsibility of operation and support and concomitant cost, he directs himself to producing items at minimum price consistent with performance requirements and profit and risk picture. This reluctance holds true for the buyer when his responsibility extends only to acquisition cost.

Although the present deployment planning anticipates systems with lifetime expectancies of 10 years, some systems may become quickly outdated, whereas others may extend considerably beyond a 10-year life cycle. A decision must be made between alternatives at a point when support costs are somewhat uncertain. Even in view of this uncertainty, the decision providing least total expected cost is based upon both acquisition and support costs over the expected system life.

Reliability estimation techniques and maintainability techniques have reached a state-of-art which permits relatively accurate estimates to be made of demands for service and service time.

Other service times become important where remote repair is reqquired. These times affect repairable items. Error in repairable spares cost may derive from the following sources:

(1) Depot Turnaround Time

Between systems, the average time may vary significantly. This time is a major determinant of spares where depot repair is used and, to some extent, controllable through the high value item concept. Note that the repair time at depot is not usually significant, except in determining depot labor costs.

(2) Field and Organization Repair Time

For both field and organization, there are tradeoffs be-between personnel and spares in meeting operational requirements. If a cost error exists, it will arise from error in prediction of repair and failure rates.

For high usage spares, the error associated with consumable spares cost over the life of the equipment will not be significant, as the purchased quantity can be adjusted to meet experienced demand.

For low usage spares, the initial purchase may be significantly more than the expected demand over the lifetime of the equipment (see appendix VI).

In this regard, item cost is intimately bound up in production quantity. If more than one production run is necessary, the cost associated with the item based on the first production run will generally provide an over estimate of the item cost.

Cost Sources Not Anticipated to Influence Decision - The following cost sources are not anticipated to be significant.

a. Manuals.

The cost of manuals will remain relatively unaffected between alternatives.

b. Facilities and utilities.

These costs may be important in determining whether or where to repair a higher level of assembly, given that existing facilities will not suffice. The cost difference for facilities and utilities for module repair, given assembly repair, will generally not be significant between alternatives.

8. SUMMARY

The major effort in this report has been to present a concept of value and a means to its quantification in as comprehensible a manner as possible, with the aim of increasing the scope and effectiveness of conventional techniques of value engineering. As currently employed, these techniques usually emphasize re-evaluation of systems and functions to achieve reduction in the cost of end item acquisition.

The technique prescribed in this report stresses the importance of value analysis in the conceptual phase of development, the objective being to eliminate alternatives requiring unnecessary costs before these costs are incurred. In this way, systematic analysis over the total spectrum of system development makes possible value optimization with respect to total expected resource cost.

The methodology of value analysis propounded in this study adds a new dimension to value engineering as generally envisaged and practiced at the present time. It proposes better communication between and improved coordination of the various levels of the engineering disciplines and management, from the conceptual stage to end item realization. It seeks the goal of obtaining the optimum product with respect to cost in resources consistent with full realization of function objectives, or succinctly expressed, "getting the job done satisfactorily at least cost." The advantages of the technique expounded should accrue to all users, Governmental procurement entities, as well as industrial producers.

The value analysis technique introduced in this report has these basic characteristics:

a. Quantification of value consistent with established USAF specification of system utilization.

b. Value parameters which are predictable and measurable.

c. Systematic method of quantitative analysis which permits practical optimization in the "least cost" sense consistent with system value.

d. Technique structure which permits design tradeoff of discrete alternatives relating to cost and system value parameters.

e. Method of cost analysis which permits optimization with respect to total cost and is consistent with both design and operational value parameters.

f. Method of cost analysis based on difference principles, which permits decisions through dominance of one alternative over another.

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EXPLANATION OF TERMS

1. Acquisition Cost - The total cost to the Government incurred to place an item(s) in initial operation in the field. (This includes both Government and contractor cost.)

2. Black Box - A discrete, physical component (sub-unit) of an operational unit to which may be assigned a rate of failure and a time-to-repair, and which may be moved from one location to another independent of the next higher level of assembly.

3. Confidence Level - A level of protection afforded against having a demand for an item out of stock. The confidence level is computed based on the probability of having one or more demands for an item, in a specified period of time, above the stock level.

4. Constraint - Any restriction or condition which bounds the value a variable or paramoter may assume; e. g., manning must not exceed 100 men. For example, number of men available and training facilities available frequently act as constraints on the training program which can be undertaken to obtain a particular number of men with particular skills.

5. Cost-to-go - The actual cost to complete the remaining program requirements.

6. Design Alternative - An alternate design layout of modules and higher modular assemblies, types, and sizes within an equipment.

7. Design/Support Alternative - An alternative involving a change in a design configuration and/or a maintenance plan.

8. Downtime - Time during which the operational unit or subsystem is not available for operational use because of maintenance or other factors.

9. Estimate-to-go - An estimate of the actual cost-to-go.

10. Exponential Distribution - A probability distribution having the form

$f(t)=\frac{1}{u}e^{-tu}$ $u>0$, $t\geq 0$, frequency distribution

$F(t)=1-e^{-tu}$ cumulative distribution

where the mean and standard deviation are both $1/u$. In this report the time between failures of equipment and time to repair failures both are assumed to be distributed exponentially.

11. Fabrication - Fabrication means the construction of a system, equipment, assembly, etc., from its parts or elements.

12. Failure Rate - Number of failures (non-scheduled interruptions of operation) of the item per unit time.

13. Imputing - Imputing, as used in this report, describes derivation of a characteristic in terms of measurable parameters.

14. Inventory - Stock (items) provided in anticipation of demand.

15. Inventory Model - A mathematical model purporting to describe relationships between allocation of spares and cost in support of an end item equipment and the military mission of the equipment.

16. Levels of Assembly - A rough measure of the size and/or complexity of a sub-division of an equipment. Except for the lowest level of assembly, the part, each level of assembly is made up of several members of lower levels of assembly. Below are listed, from high to low level of assembly, two examples of various levels of assembly.

Aircraft	Radar set
Engine	Rack
Cylinder assembly	Drawer
Cylinder head assembly	Printed-wiring board assembly
Exhaust valve	Resistor

17. Line Item - An item of supply which is listed in a Federal Stock Catalog, and to which is assigned a Federal Stock Number.

18. Logistics - The science of allocating resources for support of military operations.

19. Logistic Model - A mathematical model purporting to describe the relationship between the allocation of spares, personnel,

maintenance capability and cost, in support of an end item and the military mission of the item.

20. Maintainability - Ease of repairing an item given a particular combination of maintenance equipment and replacement parts and sub-assemblies. Generally measured in terms of mean-time-to-repair (MTTR) or its inverse repair rate (μ).

21. Maintenance Channel - Combination of men and equipment required to perform a particular task or groups of tasks.

22. Maintenance Plan - See Support System.

23. Manning Requirements - A detailed breakdown of the manning required to meet specified operational requirements of a new weapon system.

24. Manufacturing - Manufacturing is used to define the processes of procurement of parts or materials, and their fabrication into systems, equipments, etc.

25. Maximum Allowable Downtime - Time that a system may remain inoperative for the performance of a maintenance task.

26. Mean Time Between Failures (MTBF) - Average time per item between occurrence of failures. May be estimated by dividing time by the number of failures occurring during this time. It is the reciprocal of the mean failure rate (λ).

27. Mobility - A measure of how quickly the system/equipment can be relocated.

28. Module - Lowest level of plug-in assembly.

29. Module Configuration - A particular design layout of modules within an equipment.

30. Module Size - The average number of parts per module.

31. Operational Readiness - The average percent of on-line units which are operational at a given time when they are intended to be.

32. Operational Requirements - A statement of operational readiness level required of the operational units, total operational

hours, capability of the operational units during a specified period of time, and the number of missions required of the operational unit during the specified period.

33. Organization - As used in this report, organization designates the using location of an end item, or the first level of support in a multi-echelon support system.

34. Parameter - A quantity to which may be assigned arbitrary values, as distinguished from a variable, which assumes only values that the form of the function makes possible. For example: the operational readiness specified. Values may be arbitrarily assigned.

35. Personnel Availability - A measure of resources of men and skills that are available outside the system to man the system.

36. Phase-out period - The period commencing with the time of relaxed operational requirements charged to a system until complete disuse or salvage of the system and associated hardware.

37. Preventive Maintenance - The care and servicing by user personnel for the purpose of maintaining equipment in satisfactory operating condition by providing for systematic inspection and correction of incipient failures, either before they occur or before they develop into major failures.

38. Primary Duty Assignment - The type of duty to which personnel are allocated during their normal on duty shift period, and which is directly connected with the operation and maintenance of the weapon system.

39. Production - Production includes the functions of procurement, fabrication, production engineering, and other ancillary functions required for the transition from the design to the fabricated product.

40. Provisioning - The initial and continued allocation of spares in the support system of an item.

41. Quantification - The process of establishing a numerical evaluation procedure to measure a characteristic of a system.

42. Queue - A waiting line of units which require some form of service (normally maintenance repairs).

43. Ready Inventory - Spare items which are used as replacements upon failure and which are repairable at using locations.

44. Repair Rate - The reciprocal of the average time spent per channel in repairing an item, excluding delays such as "wait for spare part to be delivered," etc.

45. Repair Channel - See Maintenance Channel.

46. Skill Levels - The classification system used to rate maintenance personnel as to their relative abilities to perform maintenance.

47. Spare(s) (noun) - Systems, equipments, black boxes or modules kept in reserve, unused until needed to replace a similar failed item, so that there will not be a reduction of the number of operational systems of equipments. When the failed item is repaired, it becomes a spare if it is not needed to provide the desired number of operational systems or equipments. Not to be confused with spare parts.

48. Spare Parts - Non-repairable items at lowest level of assembly held to replace similar items whose failure caused failure of a higher level of assembly.

49. Subassembly - Of modular construction, any of several possible levels of assembly ranging from subsystem to module.

50. Subsystem - Major functional equipment or group of equipments of operational unit or support system, essential to operational completeness.

51. Service Rate - The reciprocal of mean time to restore an item to operable status, including waiting and travel time.

52. Support Alternative - An alternative maintenance plan.

53. Support System - The maintenance personnel, equipment, spares, and spare parts as organized into shops, echelons, with assigned responsibilities.

54. Tradeoff - The balancing of two or more variables associated with performance to obtain a greater return per unit cost invested.

55. Unreadiness: The fraction of time per unit time an end item equipment is not operable.

56. Utilization Factor - A ratio, the failure rate of an item, divided by the repair rate of the item. Queuing tables are usually based on the utilization factor, since it is invariant with changes in number of operational items and repair channels.

57. Value - Value is defined as the imputed quality of usefulness for a specific purpose ("imputed here describes derivation of a characteristic in terms of measurable parameters).

58. Value Analysis - Value Analysis is the systematic application of techniques used to assess the value of a system or portion of a system.

59. Value Engineering - Value Engineering is a field of engineering directed to development of systems having appropriate or specified values in the accomplishment of their missions.

60. Variable - A quantity that may assume a succession of values that need not be distinct, but which can only assume those values that the form of the function makes possible.

61. VART - Value Allocation Review Technique. A technique directed to enabling the assignment of value and cost goals to a project, permitting program review and directing value improvement and/or cost reduction.

62. Workload - Average manhours of effort of a particular skill caused by the operation of an item or group of items when they are operated according to specified requirements.

MAJOR SYMBOLS

A = Acquisition cost

C = Number of repair channels.

c = Cost designator

D = Debit and credit cost - used for inventory accountability at the depot.

D = Units down in excess of spares.

d = Fraction of units down in excess of spares.

E = Total number of equipments.

F = Number of field sites.

G_{ij} = Number of personnel of subsystem skill (i) at location (j).

I = Line item entrance cost.

L = Expected equipment life.

L_p = Equipment phaseout period.

M = Cost per year of maintaining a line item in the supply system.

N = Number of equipments per location.

N_i = Number of line items introduced into the supply systems.

N_{ri} = Number of line items repaired by depot.

N_{r-d} = Total expected repair demands at the depot.

N_{r-f} = Total expected repair demands at the field.

N_{r-o} = Total expected repair demands at the organization.

n = A designator of number in defined context.

P = Utilization factor - a ratio formed by dividing an equipment failure rate by its repair rate.

$p(\ )$ = A designator of probability in defined context.

q_1 = Fraction of depot module repair demands from the field.

q_2 = Fraction of depot higher assembly repair demands from the field.

R = Cost per year of maintaining a stock item on the Material Repair Schedule (MRS).

r_1 = Fraction of depot module repair demands from organization.

r_2 = Fraction of depot higher assembly repair demands from organization.

S = Support and operation cost.

s = Designation of spares.

T = Total cost.

t = A designator of time in defined context.

u = Operational unreadiness - the mean number of equipments not operable divided by total number of equipments.

V = Value

W = Worth

Y = Number of organizational sites per field shop.

λ = Failure rate, reciprocal of mean time between failure (MTBF).

μ = Repair rate, reciprocal of mean time to repair (MTTR), or service rate, depending on context.

APPENDIX I

NOTES ON SELECTIVE APPLICATION OF VALUE ANALYSIS

In general, most systems exhibit a non-uniform cost pattern similar to the economist Pareto's Law* on the non-uniform distribution of wealth. Relatively few system elements will be found to account for a high percentage of system cost. Generally, proportionate value improvement effort should be devoted to these items, in keeping with the principles of management by exception. The cost variation analysis procedure provides a tool to implement these principles. In establishing the initial cost estimate, particular attention should be directed to the items having the highest "cost sensitivity," namely, potential return for effort expended. Criteria to consider are:

1. High Quantity Repetitive Items - These are frequently of low or medium cost. The quantity factor exerts high "leverage" in terms of overall savings for efforts expended.

2. Standard vs. Special Items - Standard and special designs should be evaluated to determine if total value will benefit from an exchange of roles. Improved value may result from substituting a standard or Government-furnished item for a non-standard or contractor-furnished item, or vice versa.

   Standard parts tend to be less value-sensitive because they have the protection of status. A non-standard part is handicapped because it bears the burden of demonstrating at least equivalent function and reliability, and savings which will more than compensate for changes in the logistic system. On the other hand, the problem is often oversimplified and misstated, e.g., a specification for "The maximum use of authorized parts, materials, and processes." This is essential up to the point where it provides superior total value. If the use of a non-standard part can be shown to contribute greater overall value, it will have achieved the objectives of standardization by not standardizing.

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* Vilfredo Pareto - Manuale d'Economia Politica, 1906.

3. Technical Uncertainties - The scientist and engineer inherently generate value. They take the first and biggest step by making it possible to perform a function that did not exist before. During the project development plan (PDP) stage, value engineering techniques assist the inventive process and guide it to less costly solutions. In this regard, high cost areas of technical uncertainty should be investigated, particularly where the alternatives differ widely in cost.

4. State-of-the-Art - A "design from scratch" is invariably more complex, costly, and less reliable than it can ultimately be. Its value improvement potential is, therefore, higher than that of a mature design. Conversely, areas in which technology is conventional and equipment design is relatively mature, such as power supply, storage, and conversion, may be found to offer less potential. This is not necessarily so because the mature design represents the ultimate in simplicity, but because of the problems previously noted.

In addition to the criteria above, the following checklist provides an indication of potential sources of cost reduction to achieve value/cost goals.

A. SPECIFICATION REVIEW

1. Review performance specifications to ensure that no unnecessary or excessive requirements are imposed.

2. Has the cost of any overdesign been defined for its effect on production, as well as on the Research and Development program?

3. Has the cost effect of contract-required overdesign been discussed with the customer?

B. ELECTRONIC DESIGN

1. Does the design represent optimum electrical simplicity?

2. Is circuitry overly complex or conservative?

3. Have standard "preferred circuits" been reviewed to see how many can be used beneficially?

4. Has the field of commercially available packaged circuits, power supplies, etc., been reviewed against your requirements?

5. Can circuitry be eliminated by having one circuit do the job of two or more?

6. When specifying special component parts, have potential vendors been consulted for alternatives or modifications that would hold costs down?

7. Have all high cost components such as transistors, semi-conductor diodes, magnetic and high power devices, motors, gear trains, and decorders been examined to determine whether lower cost substitutions can be made?

8. Are the components of the lowest cost meeting the design requirements?

9. Can any electrical tolerance be liberalized to allow specification of lower cost parts?

10. Have nearly identical parts been made identical to gain the advantage of quantity buying or manufacture?

11. Has coaxial cable been specified, when hookup wire or shielded cable will do the job?

12. Have automated techniques been used to the maximum?

13. Is Teflon wire specified, where other insulation will suffice?

C. MECHANICAL DESIGN

1. Does the design represent optimum mechanical simplicity?

2. Is every part absolutely necessary? Can any part be eliminated or combined with another part to reduce total number of parts and cost?

3. When specifying special parts, have potential vendors been consulted for alternatives or modifications that would hold costs down?

4. Are mechanical tolerances within the limits of normal shop practice? Can any tighter tolerance specified be changed or be liberalized to hold costs down?

5. Are the surface finishes the coarsest that will do the job?

6. Are the fabrication processes of the lowest cost meeting the design requirements?

7. Have nearly identical parts been made identical to gain the advantage of quantity buying or manufacture?

8. Are the materials of the lowest cost meeting the design requirements?

9. Does the combination of material and protective finish specified result in the lowest cost combination?

10. Has relative workability of materials been considered?

11. Have standard alloys, grades, and sizes of stock been specified whenever possible?

12. Can the design be altered in any respect to avoid the use of non-standard tooling?

13. Has the 1/10-inch grid drafting system for sheet metal parts been used wherever applicable?

14. Can the design be modified to enable the use of the same tooling for right- and left-hand, or similar, parts?

15. Are drawings for fabrication of parts which are similar to parts already produced cross referenced, so that available tooling can be used?

16. Can the design be altered to avoid unnecessary handling and processing resulting from such things as riveting and spot welding of the same subassembly part?

17. Have automated techniques been used to the maximum?

18. Are casting bosses of adequate size, considering the large tolerances which apply to casting dimensions?

19. Can cores or complex parting lines be eliminated from any casting by moderate redesign?

20. Is impregnation of castings specified when it would aid processing? (Castings should be impregnated after machining, if they are to be electroplated. This impregnation prevents absorption of plating acids or salts. Castings should also be impregnated, if they are to hold liquids or gases under pressure).

21. Have engineering and factory specialists been consulted for castings, forgings, weldments, heat treatment, and other specialties?

22. Have standard sizes, grades, and alloys of fasteners been specified whenever possible?

23. Are all manual welding operations specified absolutely necessary? Can furnace brazing be substituted?

24. Are the assembly processes of the lowest-cost meeting the design requirements?

25. Has adequate clearance between parts been provided to allow for easy assembly? (Parts have become smaller, but hands have not.)

26. Are all parts designed for assembly at the earliest possible time? Assembly costs go up as the buildup of the system progresses.

27. Are markings adequate to guide the assembly processes?

28. Have the engineering and factory specialists been consulted on any unusual assembly problems?

29. Has datum line rather than multiple surface dimensioning been used on all drawings?

30. Can any four-place dimension be changed to a three-place dimension?

31. Can any three-place dimension be changed to a two-place dimension?

32. Can heat treating after forming sheet metal parts be eliminated by change of design or material to avoid straightening problems?

33. Is all masking from finishing materials (such as plating solutions and paint) necessary?

D. STANDARDIZATION

1. Have you coordinated your design with those who may be using (or have used in the past) similar designs, circuits, parts, or components, to get optimum benefit from standardization and past experience?

2. Are the standard circuits, standard components, and standard hardware the lowest cost standards which will supply the minimum required characteristics?

3. Can the use of each non-standard part of circuit be adequately justified?

4. Can any new non-standard part be replaced by a non-standard part which has already been approved?

5. Do control drawings leave no question that a vendor standard part is being specified when such is intended?

6. Has standardization been carried too far until the cost of excess function is greater than the gains resulting from high quantity?

E. MAINTAINABILITY DESIGN

1. Is each assembly self-supporting in the desirable position or positions for easy maintenance?

2. Can assemblies be laid on a bench in any position without damaging components?

F. TESTING

1. Are the test processes of the lowest cost meeting the design requirements?

2. Can any test specification be eliminated or relaxed?

3. Have interacting controls been eliminated, or the adjustments specified in such a manner that the lowest cost factory test personnel can easily align the circuit?

4. Is the system compatible with the requirements for checkout in the factory, if not as a complete system, then in large subsystem segments?

5. Have the test process experts been consulted for alternatives that would keep their costs down?

G. PRODUCTION COSTS

1. Are the quantities to be built on this order known? Are the estimated quantities to be built on future orders known? Have these factors been considered in the design decisions?

2. Will tooling costs be in line with present and anticipated production?

3. How much do you estimate the design will cost in production?

H. SUBCONTRACT ITEMS

1. Has the field of commercially available packaged units, subassemblies, and circuits been thoroughly reviewed to be sure there are no standard vendor items that will do the job?

2. Is desired cost control adequately emphasized in subcontract specifications?

3. Have our specifications for subcontract items been reviewed against the check list, to be sure we are not overspecifying?

4. Have suggestions been invited from prosepctive suppliers regarding possible value improvement from loosening specification limitations?

APPENDIX II

VALUE MODELING

1. INTRODUCTION

The model described in section 2, paragraph 2.2.3, of this report was developed for the purpose of quantifying value. It is directed to establishing value relative to a potential single requirement. Subsequently, the weighting functions (imputed probability and gain and loss functions) are removed, and the measure of achievement of value is reduced to achievement of a specified effectiveness function, which is described in terms of measurable and specified parameters. The purpose of this appendix is to develop further the generality, the basic concept developed in paragraph 2.2.

2. GENERALIZATION OF THE VALUE CONCEPT

In paragraph 2.2, value of a function was developed as:

$V(f) = p(f)\ w(f)$, which is identifiable with the system value through $V(f) = p(f)\ w(f) = \frac{V_f(s)}{p_f(s)}$, and

$V_f(s) = p_f(s)\ V(f) = pf(s)p(f)w(f)$.

In general, a system may have multiple mission requirements, and establishment of the total value of the system is desirable. This generalization can be accomplished by summing the value returns from the spectrum of mission requirements:

$$V_f(s) = \sum_i V_f(s)_i = \sum_i p_f(s)_i p(f)_i w(f)_i \ . \qquad \text{(II-1)}$$

Note that $p_f(s)_i$, $p(f)_i$, and $w(f)_i$ may vary with the mission requirement. This expression may be used as a means of evaluating competing hardware systems.

Where systems differ in deterrent capability or mission spectrum, the military value model must be invoked.

2.1 Military Value Model

This model is generalized similarly to the above development by introducing the subscript ($_i$) to designate mission type.

Thus, $V(s) = \sum_i q_i r_i W(L)_i - r_i (1-V)_i p(f)_i W(L)_i - r_i v_i p(f)_i W(L')_i$. (II-2)

Where competing systems are being evaluated over a mission spectrum, it will generally be necessary to allocate missions or functions to a mix of systems, thus creating an optimum mix. Several optimizations techniques are applicable. For unconstrained mix problems,

optimization of system value with respect to resource cost can be accomplished using the ranking procedure, which is based on selection of an alternative providing the greatest return in value per unit resource cost expended.

3. GENERAL VALUE FUNCTION

Problems of dimensionality have plagued investigators seeking a value model which permits establishing ratios to determine "greater than or less than" conditions. The following development shows the characteristics which such a function must possess to satisfy a ratio test, viz., if

$$\frac{V_1/T_1}{V_2/T_2} < 1 \quad , \qquad \text{(II-3)}$$

then V_2/T_2 is preferable to V_1/T_1, etc., where V_1 and T_1 correspond to the value and total expected cost of alternative 1, and similarly, V_2, T_2 correspond to alternative 2.

4. REQUIREMENTS OF A GENERAL VALUE FUNCTION

Let $\alpha_1, \alpha_2 ..., \alpha_n$ represent values of parameters describing a design alternative, and let V, a function of the parameters, be the value of the design alternative. The function $V(\alpha_1, \alpha_2 ..., \alpha_n)$ is to be determined, which expresses the relative (or absolute) value of the design alternative. An alternate design is described by parameter values $V(\beta_1, \beta_2 ... \beta_n)$.

If it is required that the ratio

$$V(\alpha_1, \alpha_2, ..., \alpha_n)/V(\beta_1, \beta_2, ..., \beta_n)$$

be independent of the units of measurements, then V must be of the form

$V = (\alpha_1^{a_1}) \quad (\alpha_2^{a_2}) \ldots (\alpha_n^{a_n})$, where a_i is a constant and independent of α_i, and weights the significance of α_i. The exponent may be either positive or negative.

5. THE PROBABILITY DISTRIBUTION FUNCTION

One function which satisfies the difficulties of dimensionality is the probability function. The basic requirements are satisfied if

a. The probability density function is

$$p(t) \geq 0 \text{ , and} \qquad \text{(II-4)}$$

b. The probability distribution function is

$$\int p(t)dt=1. \qquad \text{(II-5)}$$

Note, also, that the probability distribution function

$$p(t \geq t_0) = \int_{t_0}^{t} = p(t)dt \qquad \text{(II-6)}$$

is, of course, dimensionless.

Thus, the probability function approach does satisfy the dimensionality difficulties. The value engineering structure proposed in the methodology developed is compatible with the notion of measuring value in terms of a probability function.

If value is expressed in terms of effectiveness as a compound probability function, then the following relations can be logically developed:

Let

$$E' \ (e_1, \ e_2, \ \ldots e_n)$$

be a probability density function, and by definition

$$P\ (E) = \int \ldots \int E' \ (e_1, e_2, \ldots e_n) de_1, \ldots de_n, \qquad \text{(II-7)}$$

and

$$P(E \geq E_0) = \int \ldots \int E' (e_1 \ldots e_n) de_1 \ldots de_n, \qquad \text{(II-8)}$$

where

$$P(E) = \int p(e) de$$

$$1 \geq \int p(e) de \geq 0$$

and designate a specifiable and measurable system performance parameter. This equation may be interpreted to state that the value of a system can be evaluated by the probability that the system will perform under the spectrum of mission requirements over the expected lifetime of the system. Each major system performance parameter is assumed to be a function of several descrete design-decision alternatives:

$$e_i = e_i \ (\alpha_1, \alpha_2 \ldots \alpha_j \ldots \alpha_n). \qquad \text{(II-9)}$$

Each design-alternative is related to resource cost

$$c_j = c_j \ (\alpha_j), \qquad \text{(II-10)}$$

i.e., the total resource cost to implement the jth design alternative over the lifetime of the system. The design alternatives represent a set of alternatives, one or more of which is selected for

incorporation into the design of a system, and generally, each alternative will affect one or more performance parameters and the system cost. The formulation above lends itself to systematic quantitative tradeoff analysis of value. Let a change in the effectiveness relation be as follows:

$$\Delta E = \Delta E(e_1, e_2 \ldots e_i \ldots e_n); \tag{II-11}$$

then the rate of change of value is evaluated by

$$\frac{\Delta E}{\Delta C} = E'(e_1, e_2 \ldots e_i \ldots e_n) \quad \frac{\Delta e_i}{\Delta C} \tag{II-12}$$

The selection of a specific design alternative will generally affect more than one system value parameter as follows, from equation (II-12):

$$\Delta E = \sum_i \frac{\partial E}{\partial e_i} \quad (e_1, e_2 \ldots e_n) \quad \Delta e_i \tag{II-13}$$

A special case is when only one of the parameters and its associated resource cost for incremental improvement are involved in the decision, i. e., the impact of a design alternative affects a single parameter.

6. VALUE ANALYSIS DECISION MECHANISMS

6.1 Value Analysis of Function

It has been established in the preceding material that relative value may be represented in terms of the functional

$$E = E(e_1, \ldots e_i, \ldots e_n). \tag{II-14}$$

In general, the process of selection between two candidate design/support alternatives may involve each value parameter of a system being affected. That is, for alternative (a), a change in system value is introduced and evaluated from

$$\Delta E_a = \sum_i \frac{dE}{de_{ia}} \quad \Delta e_{ia} = \sum w_{ia} \; e_{ia}. \tag{II-15}$$

Similarly, for alternative (b),

$$\Delta E_b = \sum_i \frac{dE}{de_{ib}} \quad \Delta e_{ib} = \sum w_{ib} \; \Delta e_{ib}. \tag{II-16}$$

In general, the value (effectiveness) function will not be completely known, i. e., equation II-14, hence it will usually be necessary to compute, $\frac{dE}{de}\Delta e$ through modeling and parameter estimation.

This will be necessary because the rate of change of value, as related to a specific parameter (the marginal return), will depend upon the value already achieved. Figure II-1 shows in matrix form the array of interactions possible from the introduction of a design/support alternate. The first column shows the return in system value from selection of an alternative, as measured by the change in effectiveness. Each element of the column indicates the weighted return from a specific parameter change inherent in the alternative being evaluated. The succeeding columns designate the cost areas affected, given that the alternate is incorporated in the system. Summing all of the cost columns yields the total change in cost as a result of selecting the alternative. A second alternative is analyzed in a similar manner. If the alternatives are competing, the choice may be made by evaluation of

$$\Delta E_a/\Delta T_a \quad \Delta E_b/\Delta T_b \leq 1, \qquad \text{(II-17)}$$

where the Δ designates incremental changes in the value and cost (T) of alternatives (a) and (b).

Consider, for example, a system described as follows:

$$E = e_1 . e_2, \qquad \text{(II-18)}$$

where

e_1 = operational readiness, and

e_2 = mission reliability.

It is desired to determine the change in effectiveness due to a modification affecting e_1 and e_2 through a change in failure rate and repair time. Then

$$\Delta E = e_1 \Delta e_2 + e_2 \Delta e_1 . \qquad \text{(II-19)}$$

Operational readiness is given by

$$e_1 = 1/(1+\lambda_1 t_1). \qquad \text{(II-20)}$$

EVALUATION OF FUNCTION MATRIX

Incremental value return	Cost Elements Acquisition		Cost Elements Operation and Support	
	Non-Recurring	Recurring	Non-Recurring	Recurring
$w_i \Delta e_i$	$\ldots \Delta A_{i-nr} \ldots$	$\ldots \Delta A_{i-r} \ldots$	$\ldots \Delta S_{i-nr} \ldots$	$\ldots \Delta S_{i-r} \ldots$
$w_1 \Delta e_1$				
$w_2 \Delta e_2$				
$\vdots$				
$w_i \Delta e_i$				
$\vdots$				
$w_n \Delta e_n$				
$\Delta E = \sum w_i e_i$	$\Delta A_{nr} = \sum_i \Delta A_{i-nr}$	$\Delta A_r = \sum_i \Delta A_{i-r}$	$\Delta S_{nr} = \sum_i \Delta S_{i-nr}$	$\Delta S_r = \sum_i \Delta S_{i-r}$

Figure II-1.

and mission reliability is given by

$$e_2 = \exp(-\lambda_t t_k).$$

Now, the change introduced in operational readiness as a result of a change in the ith element is

$$\Delta e_1 = (\lambda_t \Delta t_i + t_t \Delta \lambda_i)/(1+\lambda_t)^2 \quad \text{(II-21)}$$

If e_1 is positive, the change in operational readiness is an increase; if negative, then it is a decrease.

To determine Δe_2:

$$\Delta e_2 = -t_k \exp(-\lambda_t t_k) \Delta \lambda_t \quad \text{(II-22)}$$

where

$$\lambda_t = \sum_{i=1}^{n} \lambda_i \quad \text{(II-23)}$$

λ_t = total estimated failure rate of system,

and

λ_i =failure rate of the ith element having maintenance significance, and

$$t_t = \sum_{i=1}^{n} t_i \quad \text{(II-24)}$$

where

t_t = mean repair time of system, and

t_i = contribution of ith element to system repair time.

This is approximately

$$t_i = \frac{\lambda_i \bar{t}_i}{\lambda_t} \quad \text{(II-25)}$$

where

$\bar{t}_i$ is mean time to perform maintenance on ith element failure,

and

t_k is the time of mission duration.

Consider a possible modification of the ith element failure rate λ_i to λ'_i and a concomitant change in repair time $\bar{t}_i$ to $\bar{t}'_i$.

Let $\Delta\lambda_i = (\lambda_i - \lambda'_i)$, and

$\Delta t_i = (t_i - t'_i)$.

Identify $\Delta\lambda_t$ with $\Delta\lambda_i$, and Δt_t with Δt_i.

Substituting these values into equation (II-19) and rearranging terms

$$\Delta E = \frac{\exp(-\lambda_t t_k)}{(1+\lambda_t t_t)^2}\left[t_k (1+\lambda_t t_t) + t_t\right] \Delta\lambda_t +$$

$$\frac{\exp(-\lambda_t t_k)}{(1+\lambda_t t_t)^2} \lambda_t \Delta t_t = w_1 \Delta\lambda_t + w_2 \Delta t_t .$$

The coefficients of these terms above become w_1 and w_2, respectively, and E becomes E_i, i.e., the change introduced in system value resulting from this design alternative, if selected.

6.2 Value/Cost Alternative Matrix

The matrix form for value analysis of function has its cost counterpart for hardware development, operation, and support. Figure II-2 indicates the breakdown of a system into its hardware and software elements designated by the item column. The succeeding columns designate cost differences associated with a hardware or software item change, as reflected by selection of a design/support alternative being incorporated into the system. At all times, the basis of the analysis is differences in total cost. The total cost difference from an alternative appearing in figure II-2 should be the same as that appearing in figure II-1, the only difference being one of cost analysis structure.

6.3 Cost Decision Element Matrix

In general, it will only be necessary to evaluate the difference between two alternatives; where more than two alternatives exist,

VALUE/COST ALTERNATIVE MATRIX

Hardware item/ task affected	Acquisition Cost Elements		Operation/Support Cost Elements		
	Non-Recurring ΔA_{i-nr}	Recurring ΔA_{i-n}	Non-Recurring ΔS_{i-nr}	Recurring ΔS_{i-r}	ΔT
1					
2					
⋮					
j					
⋮					
	ΔA_{nr}	ΔA_{n}	ΔS_{nr}	ΔS_{n}	ΔT

Figure II-2.

the procedure is to systematically eliminate the poorer choice alternative by direct comparison of estimated cost differences.

Figure II-3 illustrates a tabular procedure for evaluating each element of the cost model. Provision is made, in figure II-3, for the evaluation of two alternatives. Only the elements that change, from one alternative to the other, will be required. Once two alternatives have been evaluated, the one yielding a cost advantage is retained, and the other alternative is no longer considered.

7. COMMENTS ON VALUE MODELS

The following general observations are based on the preceding discussion:

1. Any model of the form

$$V = \sum_i \alpha_i x_i \; /c,$$

where α_i is a weighting factor of performance parameter x_i and c is cost, will not suffice generally as a working model, due simply to the fallacious assumption of linearity of the weighting factor.

2. To avoid problems of dimensionality, only one non-probability weighting factor can be used for value modeling, e.g., resource cost and its broad implications measured in dollars.

3. Computation of the rate of return in value per unit resource cost invested will depend on the particular alternatives being evaluated. This may require specific model development, e.g., from serial elements to redundant elements in the reliability model sense.

4. The cost incurred to achieve a specific value lies in the means of implementing the value, and not in the value per se.

Cost Element (C)	Sub-Script	Step ( ) A( )	Step ( ) A ( )
Design	D		
Fabrication	F		
Installation	I		
Manuals	M		
Test Equipment	T		
Tools and Fixtures	X		
Line Item Documentation	L		
		S( )	S ( )
Organization	o		
Personnel	om		
Facilities	of		
Spares	os		
Transportation	ot		
Field	f		
Personnel	fm		
Facilities	ff		
Spares	fd		
Transportation	ft		
Depot	d		
Personnel	dm		
Facilities	df		
Spares	ds		
Transportation	dt		
Utilities	du		
Line Item	e		
Factory	y		
Total Cost	T		
Cost Difference	T		

Figure II-3. Cost Decision Elements

2

APPENDIX III

FUNDAMENTALS OF MANNING

1. INTRODUCTION

The evaluation of alternatives of system design, including operational and maintenance concepts, requires application of a standard, objective method for determing operational support requirements. This appendix describes a method for determination of support requirements to satisfy an objective. The support requirements established include manning and skills, and repairable spares. The objective is a given level of operational readiness for a specified operational schedule. Application of the method provides support requirements in a form permitting objective comparison of system designs and of alternative policies for maintenance, which affect personnel and spares.

Emphasis will be placed upon the determination of maintenance manpower. Operational manning requirements are similarly determined, except that queuing aspects of the problem can usually be ignored.

2. OPERATIONAL READINESS

The operational readiness of a weapons system which comprises a number of operational units, e.g., 18 aircraft per squadron, is defined as the number of on-line (ready operational units divided by the total number of operational units in the system,)

$$R=\frac{N_0}{N}=\frac{N-D}{N}, \qquad \text{(III-1)}$$

where (N_0) designates operational units ready,

(N) designates operational units assigned to the system, and

(D) designates operational units down for service.

This relationship may also be expressed in terms of time:

$$R=\frac{t-t_d}{t}, \qquad \text{(III-2)}$$

where (t) designates the sum of the average uptime and downtime of an operational unit, and (t_d) designates the average downtime of an operation unit.

Generally, an operational unit will exist in one of three states:

1. In operation for a time (t_o) per day.
2. Ready for operation for a time (t_r) per day.
3. Down due to corrective or preventive maintenance (t_d) per day.

States (1) and (2) have been combined into "ready time" for the present purpose.

Operational readiness is used as a performance measure for an operational unit, or for a number of operational units. Readiness itself is a dimensionless parameter. Evaluation of a system is facilitated by introduction of an "unreadiness" parameter , (d), defined as the fraction of operational units down. If operational readiness is expressed as

$$R=\frac{N-D}{N}=1-\frac{D}{N}, \qquad \text{(III-3)}$$

Where $d=\frac{D}{N}$, it is evident that

$$R=1-d.$$

A system is comprised of a number of subsystems contributing independently to system unreadiness. Using "unreadiness", these contributions can be added to determine system operational readiness:

$$R=1-\Sigma d_i, \qquad \text{(III-4)}$$

where (R) is the operational readiness of the system, and the (d_i)'s are unreadiness contributions of the subsystems.

Each subsystem's unreadiness contribution is a function of maintenance personnel in terms of repair channels, and of spares assigned, and the implied costs of both factors are represented by

$$d_i=f(s_i, \text{ cost}; C_i, \text{ cost}), \qquad \text{(III-5)}$$

where (s_i) and (C_i) represent spares and repair channels assigned to the subsystem skill package.

Spares and personnel assignment depend upon failure and service rates, and the relative cost of spares and personnel.

$$s_i = s_i(\lambda, \mu, C_i), C_i = C_i(\lambda, \mu, s_i), \quad \text{(III-6)}$$

where (λ) and (μ) are failure and service rates.

Any change in one of the parameters above can be expected to reflect itself into a change in unreadiness (d_i). A change in unreadiness (Δd_i) can thus be measured in terms of cost. This permits tradeoff of personnel, spares, skill packages, etc., and optimization with respect to operational readiness (R).

3. THE MODEL

In order to optimize the assignments of personnel and spares, it is necessary to have a means to evaluate unreadiness (d_i) in terms of failure and service rates (λ, μ), spares (s_i), and service channels (C_i).

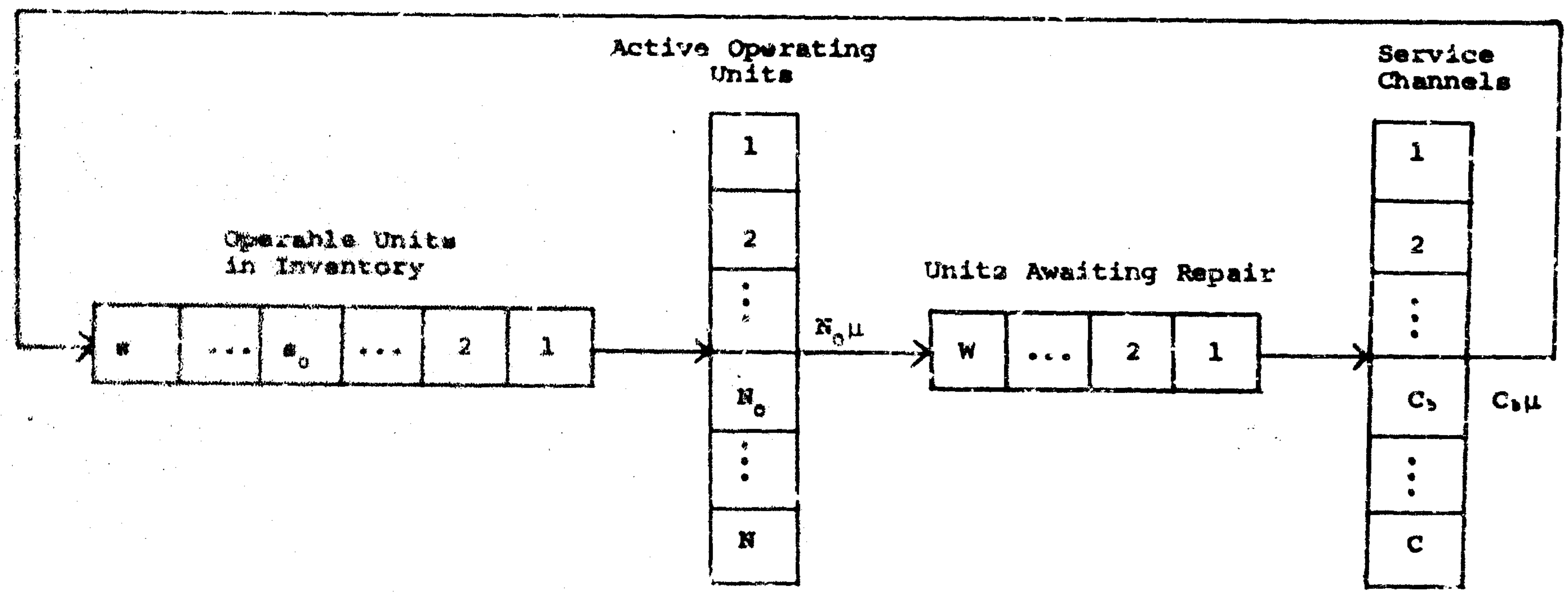
The method is based upon development of an activity network which is representative of the physical situation. The activity network provides a means of recognizing logical task allocations and their impacts upon manning. The network will be described in terms of a finite cyclical queue, which describes a process generally encountered in military, and often in commercial operations, specifically, where the operation involves repairable machines, with which a failure rate and a repair rate may be associated. Figure III-1 illustrates the behavior of a system under finite cyclical queue conditions.

The mathematics of the model is based on exponential failure and service channel rates.

Although seemingly restrictive in nature, the model provides accurate results, even in cases which vary significantly from exponential. Further, as a practical matter, the error usually associated with the estimate of measurable parameters required will exceed the lack of fit introduced by the degree of lack of fit of the exponential processes involved. Also, output error is invariably less than input error.

Spares complement, (s_i), is measured in whole units of the subsystem population (N). If the skill package is developed for a black box, (s_i) represents the number of spare black boxes; if the skill package has been assembled for a complete aircraft, (S_i) is spare aircraft. This is, of course, only an approximation to the real spares, but since sparing will really be done at a lower level of assembly, the estimated contribution of spares to operational readiness is conservative.

Operational manning requirements are normally determined upon the basis of position descriptions rather than analysis of fluctuating workload.



N = Number of operational positions

N_o = Mean number of operational positions filled

s = Spare units

s_o = Mean number of operable spare units

C = Number of service channels

C_b = Mean number of busy channels

λ = Failure rate of operating unit

μ = Service rate of service channel

W = Mean number of units awaiting service

FIGURE III-1. FINITE CYCLICAL QUEUE

2

4. PIPELINE PERSONNEL AND BACKUP FACTORS

From the foregoing, the number of personnel required to perform work in satisfaction of operational readiness can be determined. This count is based upon available personnel, and must be modified to account for sick leave, furlough, etc. This adjustment factor is 0.20 times the direct manpower by skill level, and is additive. This factor is derived from AFM 26-1.

The military manpower problem is peculiar in its high turnover rates of experienced personnel, resulting from discharges, retirements, and promotions. This necessitates placing a significant number of personnel in training for required positions. These personnel additional to basic system requirements are designated pipeline personnel.

In most technical fields, there is a series of skill levels, viz., 1, 3, 5, 7, and 9, representing increasing amounts of skill, knowledge, and responsibility. Typically, the technician advances a level at a time to the highest level, with training and the passage of time being prerequisites for each step. Consequently, in order to have men continuously in the highest level, there must be a steady upward flow from the lower skill levels to replace those discharged. Only a small portion of the qualified men starting out in a field reach its high skill levels; concomitant with this progression is a progression in grade (rank), pay, and privileges. In the succeeding analysis, the concern is to establish the total number of personnel required in personnel inventory in order to maintain a spacified number of qualified personnel assigned to a given system.

The personnel lost per year in a specific skill field (k) and skill level (i) consists of the following:

1. Discharged (D_{ik}).
2. Retired (R_{ik}).
3. Promoted (P_{ik}).
4. Transferred (T_{ik})*.

*T_{ik} can represent either a gain or loss to the system.

The total personnel leaving a skill designation (ik) per year can be represented by:

$$L_{ik}=D_{ik}+R_{ik}+T_{ik}+P_{ik}. \qquad \text{(III-7)}$$

Steady State Personnel Required by a Specific System

For designation ($_{ik}$), all personnel leaving this designation must be replaced through promotion from:

$$P_{k,i-1}=D_{ik}+R_{ik}+T_{ik}+P_{ik}.** \qquad \text{(III-8)}$$

**Using this basic relationship, the recurrence equation for a specific skill field becomes:

$$P_k=P_0-\sum_{1}^{i}(D_n+R_n+T_n). \qquad \text{(III-9)}$$

The significance of (P_0) is that it represents the number of personnel to be brought into basic training to support the personnel of a given system.

Let

g_i = personnel required in each skill level, for a given field, as determined by manning analysis to achieve system operational requirements.

l_i = the yearly rate per person of personnel leaving this skill level ($_i$).

Then, $$l_i=\frac{L_i}{g_i}, \qquad \text{(III-10)}$$

and $$p_i=\frac{P_i}{g_i}. \qquad \text{(III-11)}$$

the rate per person of personnel being promoted from the (ith) skill level per year.

Suppose a system manning analysis establishes that the Table of Organization (TO) for personnel requires (g_4), (g_3), (g_2), and (g_1) personnel in the respective skill levels. To have a self-sustaining personnel system, viz., one that produces sufficient skilled personnel from a level to replace those leaving the next in highest skill level, the equation

$$g_i l_i=g_{i-1}p_{i-1} \qquad \text{(III-12)}$$

must be satisfied. In general, these equations will not be satisfied for a given system. Thus, in general,

$$g_i l_i\neq g_{i-1}p_{i-1}. \qquad \text{(III-13)}$$

If $$g_i l_i \neq g_{i-1} p_{i-1} \qquad \text{(III-14)}$$

this requires that somewhere in personnel inventory there must be (Δg_{i-1}) additional personnel, so that

$$g_i l_i = (g_{i-1} + \Delta g_{i-1}) p_{i-1} = g'_{i-1} p_{i-1}. \qquad \text{(III-15)}$$

Transposing and adding to subscripts,

$$g'_i = (l_{i+1} g_{i+1})/p, \qquad \text{(III-16)}$$

and

$$g'_i = (l_{i+1} g'_{i+1})/p_i, \qquad \text{(III-17)}$$

and so forth, stopping at each primed (g_i) which yields the largest number. Therefore, in establishing total system personnel requirements, the number of people charged to the system in any skill level will be the greatest value of (g_i) and the primed g_i's starting with the manning analysis as represented by the TO.

Example 1

Let g_4, g_3, g_2, and g_1 designate the required skill complement as determined by a work analysis. The total number of persons needed to fill these requirements will be determined from equations III-16 and III-17.

Suppose the following data are available:

$g_4=20$	$l_4=0.30$	$p_4=0.00$
$g_3=40$	$l_3=0.40$	$p_3=0.30$
$g_2=100$	$l_2=0.85$	$p_2=0.10$
$g_1=30$	$l_1=0.98$	$p_1=0.95$
$g_0=0$	$l_0=0.99$	$p_0=0.98$

Applying:

$$g'_i, (l_{i+1} g_{i+1})/p_i, \qquad \text{(III-16)}$$

the results are:

$g'_4=-$		$g_4=(20)$
$g'_3=20$		$g_3=(40)$
$g'_2=(160)$	as opposed to	$g_2=100$
$g'_1=(90)$		$g_1=30$
$g'_0=(30)$		$g_0=0$

The larger number of persons is in brackets. Then applying equations III-16 and III-17 successively, and always choosing the largest number of persons, the following data are obtained:

Work Analysis	To be Supplied
$g_4=20$	$g_4 = 0$
$g_3=40$	$g_3 = 0$
$g_2=100$	$g''_2 \cdot g_2=60$
$g_1=30$	$g''_1 \cdot g_1=114$
$g_0=0$	$g''_0 \cdot g_0=144$
Total 190	318

Stated in words, for every group of 190 persons, as determined by work requirements assigned to the system, an additional group of 318 must be supplied to ensure skill stability, making the total number of persons required to man the system actually 508.

<u>Example 2</u>

The following rates are representative of an existing Communications and Electronics Squadron:

$g_4=14$	$l_4=0.08$	$p_4=0.00$
$g_3=48$	$l_3=0.15$	$p_3=0.8$
$g_2=106$	$l_2=0.45$	$p_2=0.05$
$g_1=26$	$l_1=0.50$	$p_1=0.40$
$g_0=0$	$l_0=0.99$	$p_0=0.98$

Using the TO as a basis for calculation:

$g_4=14$		$g_4=14$
$g_3=48$		$g_3=48$
$g_2=106$	as opposed to	$g'_2=144$
$g_1=26$		$g''_1=162$
$g_0=0$		$g''_0=83$
Total 194		451

Roughly, the personnel system requires twice as many personnel as can be actively employed, to ensure a trained reserve.

Two fairly obvious features are:

a. Reduction in level three and level four capability has a significant effect upon level two personnel. This is indicative of the fact that the higher skill levels are most likely not to be filled.

b. The critical skill level is level two, in which a high discharge rate occurs. This level also consists of independent workers. A small change in the retentivity rate of this level would have manifold benefits.

For example, suppose the leaving rate (l_2) in the example above were changed from .45 to .30, and (p_2) from .05 to .10 per year. Then the new requirements would be

$$
\begin{aligned}
g_4 &= 14 \\
g_3 &= 48 \\
g_2 &= 106 \\
g_1 &= 80 \\
g_0 &= 41 \\
\hline
\text{Total} &= 289
\end{aligned}
$$

as opposed to the TO of 194 and the requirement of 451 previously determined for steady-state maintenance of the personnel structure. The resultant saving of 162 man years per year could be invested to secure the retentivity requirements. In addition, significant savings would be realized through better trained personnel.

5. TABLES

Tables have been developed to assist in determining the number of direct personnel required to satisfy operational readiness requirements (Tables for Determining System Manning and Related Support Requirements, AMRL-64-125).

These tables incorporate the following parameters:

Tabular Entries

C= Number of service channels.

N= Maximum number of units which may demand service at a particular instant.

s= Number of spare units which may replace units being serviced or awaiting service.

P= Utilization factor (λ/μ),

where

λ= Rate of demand of one unit (failure rate), and

μ= Service rate of one channel.

Output

Two quantities are the output of the tables as follows:

d= Mean number of failed units, per N, for which no spares (s) are available.

n_d=Mean number of units, per n+s, either awaiting or undergoing service.

Defined Quantities

D = Mean number of failed units for which no spare is available, and

= dN.

N_d = Mean number of units either awaiting or undergoing service, and

= $n_d\,(N+s)$,

R = Operational readiness, and

= N_o/N,

where

N_o = Mean number of units operating,

= $N-dN = N(1-d)$

Derived Quantities

Two identities listed below are the basis for derivation of other pertinent quantities necessary to establish system measures. They are:

$$N_d = W + C_b. \tag{III-19}$$

$$C_b = N_o P. \tag{III-20}$$

This identity states that the mean number of busy channels, (C_b), is equal to the mean number of units operating, (N_o), multiplied by the utilization factor (P). This identity may be established by considering the following:

> In a steady state there exists a finite queue length. In order to maintain a stable mean queue length, the number of units entering the queue must be equal to the number of units leaving the queue. The mean number of units arriving to the queue is equal to $N_o\lambda$. Also, for steady state, the mean number leaving service (μC_b) must be equal to the mean number of units leaving the queue. Thus,

$$\mu C_b = N_o \lambda, \tag{III-21}$$

or

$$C_b = N_o P. \tag{III-22}$$

The following quantities can now be derived, using the definitions established above:

W = Mean number of units awaiting service, and
$= N_d - C_b$.

s_o = Mean number of units operable but not operating, and
$= s + D - N_d$.

t_w = Mean waiting time for service (in queue), and
$= W/\mu C_b$.

t_{ws} =Mean waiting time in waiting and service, and
$= t_w + 1/\mu$.

t_{wd} =Mean downtime, waiting for replacement of a failed unit.
$= D/\mu C_b = d(\lambda(1-d)$.

Format of Tables

The tabular format is based on anticipated use of tables. Two parameters, (N) and (P), are required to locate each specific table within the range covered. Within each specific table are two additional locators: service channels (C - columns) and spare units (s - rows). For combinations of (C) and (s), there are two output entries; these are (d), the fraction of units inoperable in excess of spares and (n_d), the fraction of the total number of units down.

The effect on the output entries (d, n_d) of changing either (C) for a given (s), or (s) for a given (C), may be read directly in sequential order; viz., across a row for (C) and down a column for (s). A particular advantage is that for a specified combination (C,s) the maximum rate of change in the (d, n_d) may be immediately determined from the difference in value between present value of (d) and (n_d) and that obtained from the adjacent row and column. The format of the basic tabular entries follows:

N = P =

s \ C	1	2	3	...
0				
1		$d =$ $n_d =$		
2				
...				

Perhaps the most important characteristic of this format is that it permits a visual evaluation of the effect or changing (s) and (C), individually, or in combination. Given cost estimates of a service channel increment and a spare unit, simple cost analysis may be performed directly from the tables.

Example - Evaluation of Operational Readiness

Two equipments may be operated as follows: one on-line, and one off-line as a spare. A maximum of two service channels (repair crews) should be available. The failure rate per equipment is 0.1/hours. The service rate per channel is 1.0/hours. The tabular parameters are, therefore,

$$N=1,$$

$$P=.1,$$

$$C=1,2, \text{ and}$$

$$s=1.$$

Turn to the section of the table with N=1 and P=.100000.

(This part of the table is reproduced below.)

N= 1 P= .10000

S \ C	1	2
0	.091 .091	
1	.009 .054	.005 .050
2	.001 .037	

Read off:

$$d_{s,c}=d_{1,1}=.009 \qquad \text{(III-23)}$$
$$=d_{1,2}=.005,$$

then

$$R_c=R_1=.991 \qquad \text{(III-24)}$$
$$=R_2=.995.$$

Suppose the spare required three minutes (t=.05 hours) to go into action upon failure of other equipment. The time would detract from the computed operational readiness by an amount (λt). Assume a total possible on-time of (t'), then the time the equipment is down (neither the equipment, nor the spare, on-line) is

$$t_d = dNt'(1-dN)(\lambda t), \qquad \text{(III-25)}$$

then

$$R' = (t'-t_d)/t' \qquad \text{(III-26)}$$

$$= (1-dN)(1-\lambda t).$$

Calculating the revised operation readiness,

$$R_1' = (.991)(.995),$$

$$= .986.$$

$$R_2' = (.995)(.995),$$

$$= .990.$$

6. OPTIMIZATION ROUTINE

For any system, maintenance may be performed at a number of locations. At each location, a number of subsystems may be maintained, with individual manning and spares complements determined through exercise of the optimization procedure, illustrated in figure III-2. An example of application is in section 7.2 of this appendix.

The manning procedure developed below is biased conservatively. That is, it tends to underestimate the operational readiness level resulting from a particular manning scheme. However, results from the field, based upon investigation of the technique's validity, establish that the procedure estimates manning at lower levels than typical T. O. establishment.

These differences result directly from differences in the techniques employed. The technique described in this report achieves conservative results through consideration of manning requirements as resulting from completely random processes. This is not strictly the case, since there is some control exercised in scheduling work. Existing methods for establishing manning T. O.'s are intimately dependent upon design similarities, and operational environment and usage. They do not deal directly

with the interrelations between the design and its application nor with pipeline personnel in its relationship to the other factors.

In point of fact, no analytical manner exists which is capable of combining all of the potentially significant task characteristics. In general, however, certain characteristics will always tend to predominate. These form the basis of the procedure which is outlined below, and developed more fully throughout this appendix.

In principle, estimation of manning requirements as a function of design parameters and operational requirements is relatively simple. The procedure consists of the following:

a. Estimate reliability and repairability of hardware items in their operating environments.

b. Weight reliability and repairability with required usage capability to determine the frequency of demand for service and the associated workload.

c. Allocate hardware items to skill packages. This consists of combining work elements having commonality of characteristics:

(1) Common work location.

(2) Common technical knowledge

(3) Common tools and test equipment.

From these characteristics, the skill speciality field is established.

d. Based upon the foregoing knowledge, estimate the number of personnel of each skill level required to perform simultaneously on the tasks comprising each skill package. This grouping of personnel is the skill team, or service channel. (NOTE: Generally, level 5 personnel constitute independent workers, and level 7 are work programmers or supervisors. Level 3 personnel work under the direction of levels 5 and 7, to accomplish less complex tasks).

e. Use the manning tables described previously to optimize the relationship between service channels and spare to satisfy operational readiness requirements. Apply backup and pipeline requirements.

Work requirements are separated by demand type and priority.

(1) Random or scheduled demand

(2) Primary or secondary priority

Random and scheduled demands are frequently associated with primary and secondary priorities, respectively. If random and scheduled demands both have primary priorities, they are grouped into the same skill packages and treated as random.

The capability for secondary workload is established by computing idle time available from primary work requirements as described in paragraph 8.1 of this appendix. If available idle time exceeds the secondary workload, then no additional personnel are required. If additional personnel are required, reexamine the tradeoff between service channels and spares.

Total personnel requirements for the system (ΣG_{ik}) consist of the aggregate of subsystem skill assignments by location, as determined through optimization. Consideration is given for contingency plans or self-sufficiency requirements, which might require separability of skill packages into smaller units (as for separation of a self-sufficient squadron from its group or wing). A block diagram of the overall manning procedure is shown in figure III-3.

7. STANDARD TRADEOFF PROBLEMS

The application of the manning procedure will involve, in general, specific standard tradeoff problems. The more important standard tradeoffs are explored in the following applications of the technique.

Inputs to Program

Specified Paramters:

Each of these parameters may be arbitrarily changed to evaluate the effect on manning requirements

N= Operational Units

R_o =Operational Readiness Required

Working Shift Duration

Number of Operations Per Shift (if not continuous capability)

Usage Duration Per Operation

Measured or Predicted Parameters:

λ_i = Failure Rate of subsystem

μ_i Repair Rate of sybsystem (assigned to skill package type per operational unit)

Scheduled Workload Per Channel Per Operational Unit.

Secondary Workload Tasks Assigned to the Skill Package

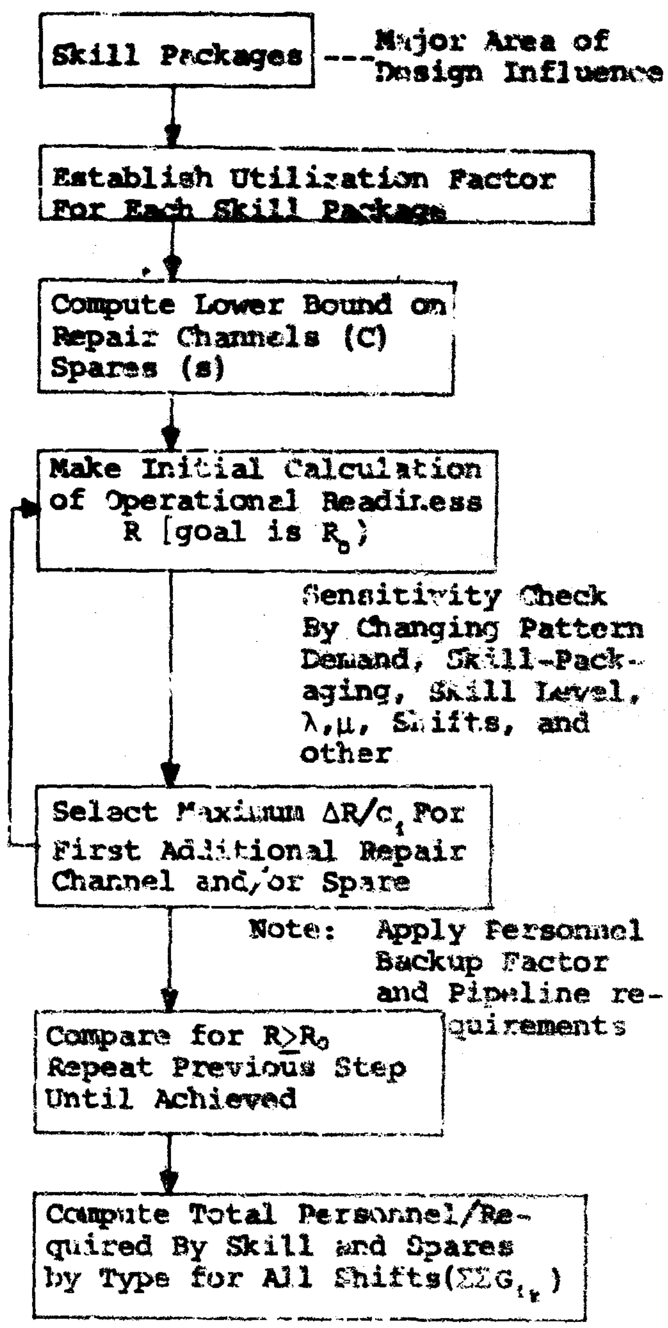


Figure III-2 Optimization Routine: Flow Chart Summary

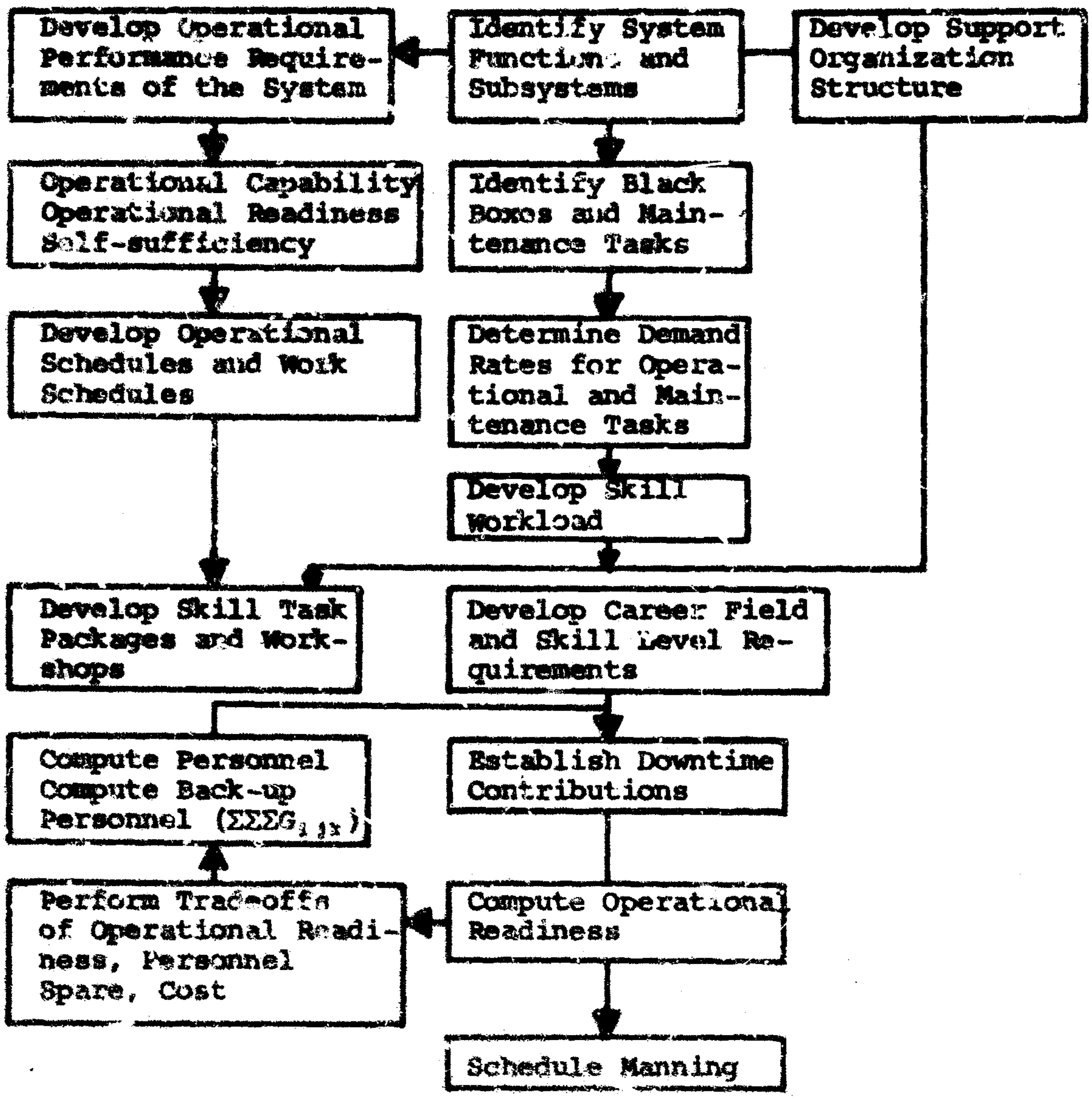


Figure III-3. Manning Routine Block Diagram

7.1 Multi-shift Schedule, Pipeline Personnel and Backup Factor Application

System Manning - A shop responsible for overhaul of jet engines will be considered for a wing of 40 four-engine aircraft. Periodically, after a given number of hours of flying time, all four engines are removed and replaced from ready spares, if available.

The overhaul operation requires one man of skill level (7) and one of skill level (5).

The basis for consideration of multi-shift operation is recognition of the necessity for a common time base for demand and service rates. In this example, because the operational and maintenance schedules are on five-day weeks, a daily basis for failure and repair rates is suitable. A two-shift maintenance schedule, however, provides twice as much repair time per day as a single shift schedule. This results in a utilization factor (P) for two-shift maintenance, corresponding to one-half the one-shift value (see paragraph 8).

The utilization factor is given at (P_1=.10) for two shift maintenance, and (P_2=.20) for one shift.

The operational readiness levels to be investigated are (R_1=.90), (R_2=.95), and (R_3=.98). The table below gives combinations of maintenance teams (C) and sets of engine spares (s), satisfying (R_1), (R_2), and (R_3), respectively (these are obtained from the queuing tables N=40, P=.1 and P=.2).

TABLE III-1

	R_1		R_2		R_3	
Two Shift	C	s	C	s	C	s
P =.1	6	0	7	2	7	4
	5	1*	6	3	6	5*
	4	4	5	4*	5	7
	3	14	4	13	4	16
One Shift	12	4	13	5	13	9
P =.2	9	5	10	7	11	10
	8	7	9	9	10	11
	7		8	16	9	15

Assume that the annual cost of a repair channel equals the annual cost of a spare set of four engines. To find the minimum cost for each (R), it is only necessary to find the minimum total of (C+s).

These values are indicated above by underlined entries. The (C) entry must be multiplied by the number of shifts to obtain total cost. The optimum policy, which is indicated by an asterisk, call for two shifts, in all cases.

An adjustment to each repair channel must be performed to compensate for sick leave, furlough, etc. (this is taken to be 0.2, see appendix VIII). Additionally, personnel are required in the system to replace other personnel leaving due to discharge, etc., as a stable personnel system is required. To achieve this, suppose that the number of men at skill level (5) must be equal to, or greater than, that at level (7). For every two (5) level personnel, one (3) skill level person and one trainee are required. Since the repair team consists of one each at levels (7) and (5) skill, no additional (5)'s are required. However, for each (5) level, one additional man is required, i.e., 1/2 (3)-level, 1/2-trainee (T).

Requirements for optimal policies are tabulated below.

TABLE III-2

	R_1=.90				R_2=.95				R_3=.98			
Skill Level	7	5	3	T	7	5	3	T	7	5	3	T
Personnel	10	10	5	5	10	10	5	5	10	10	5	5
Adjust by .2	2	2	1	1	2	2		1	2	2	1	1
Total	12	12	6	6	12	12	6	6	12	12	6	6
Resource Cost	11 units				14 units				17 units			

In the examples which follow, pipeline personnel and backup are not considered.

7.2 Application of the Optimization Technique

A standard operation in military and industrial operations is the periodic calibration of test equipment, and repair and recalibration of failed test equipment. Suppose a type of test equipment is required to be calibrated every month (x=30 days). These test sets are used by 10 repair teams (N=10). It takes 10 days for the calibration or the repair and recalibration action (y=10 days.). The test set has a mean time between failure

of 6 months ($t'=180$ days).

A tactical requirement is that 8 of the 10 repair teams must be operable ($N_o=8$). It is possible to vary the number of service channels (C) and/or the number of spare test sets (s) to satisfy the tactical requirements.

Before using the tables, it is necessary to determine (P). Let the mean arrival rate of a test set into the repair shop be approximated by

$$\lambda=t'/[x(t'-X/2)],^{*}\ t'>x \qquad \text{(III-27)}$$

and

$$\mu=1/Y,$$

so that

$$P=\lambda/\mu,$$

$$=.364,$$

$$\cong .350.$$

Turn to the section of the table with (N=10) and (P=.35000). Indicated below are the possible combinations of (C) and (s) to satisfy the tactical requirement ($N_o=8$):

C	s
3	5 or more
4	2 or more
5	1 or more
6	1 or more

It may be of interest to determine a least cost method of achieving N_0 in the preceding example.

Let the total cost equation be

*If $\lambda=1/x$, the quantity would correspond to mean arrival rate for calibration only.

$$a = Ab + Ce(N+s)f, \qquad \text{(III-28)}$$

where

a= Total cost,

b= Cost of a repair team, e.g., \$25,000/year,

e= Cost of a calibration/repair channel, e.g., \$5,000/year, and

f= Cost of a test set, e.g., \$1,000/year.

All are expressed in cost per unit time. It is known that $N > N_0$, $C \geq 1$, and $s \geq 0$.

The change in the total expected cost per change in number of repair teams is

$$\Delta b_a = b + f, \qquad \text{(III-29)}$$

where the associated change in number of repair teams is symbolized by ΔN_{0-a}.

Similarly, for calibration/repair channels,

$$\Delta e_c = e \qquad \text{(III-30)}$$

and ΔN_{0-c},

and, for spare test equipments,

$$\Delta f_s = f \qquad \text{(III-31)}$$

and ΔN_{0-s}.

Starting from

$$a_1{}^{*} = (N_0+1)b + 3e + (N_0+1)f, \qquad \text{(III-32)}$$

compute ΔN_{0-a}, ΔN_{0-c}, and ΔN_{0-s}, using the numbers from example 2.

---

* a_1=\$249,000 with C=min 3.

For a change in the number of repair teams,

N=9	P=.35	C=3	s=0	d_1=.302
N= 0	P=.35	C=3	s=0	d_2=.319

$$\Delta N_{o-n} = N_2 R_2 - N_1 R_1 \qquad \text{(III-33)}$$
$$= .528.$$

For a change in the number of calibration/repair channels,

N=9	P=.35	C=3	s=0	d_3=.302
N=9	P=.35	C=4	s=0	d_4=.266

$$\Delta N_{o-c} = d_3 - d_4 \qquad \text{(III-34)}$$
$$= .034.$$

For a change in the number of spare test equipments,

N=9	P=.35	C=3	s=0	d_5=.302
N=9	P=.35	C=3	s=1	d_6=.247

$$\Delta N_{o-s} = d_5 - d_6 \qquad \text{(III-35)}$$
$$= .055.$$

Forming the ratios as follows

$$\Delta N_{o-n}/(b+f) = 2.03\text{x}10^{-5},$$
$$\Delta N_{o-c}/e = 6.8\text{x}10^{-6}, \text{ and}$$
$$\Delta N_{o-s}/f = 5.50\text{x}10^{-5},$$

choose the ratio $\Delta N_{o-s}/f$ as representing the maximum incremental return per unit cost investment. Stated in another way, if (N=9), (C=1), and (s=0), the least costly action is to increase s by 1, in order to approach the tactical requirement of 8 out of 10 active repair crews.

The reference point of the second computation cycle is established by the selection made by means of the first cycle, viz., increase (s) by 1. The table below shows the result of carrying through this analysis.

Computation Cycle	N	C	s
Start	9	3	0
1	9	3	1
2	9	3	2
3	9	3	3
4	9	3	4
5	9	4	4
Stop			

7.3 Approximation Techniques to Two Levels of Maintenance

The tables are exact for one level of maintenance. However, a very good approximation to the manning problem, on two levels of maintenance, can be made using the tables. Alternative procedures to be used are given in succeeding paragraphs.

Typically in the United States Air Force, a weapons system, such as an all weather fighter - interceptor, will depend upon a number of distinct maintenance shops to maintain it in a state of operation or readiness. For the most part, these shops, along with the particular subsystems they support, will independently contribute unreadiness to the weapons system. Furthermore, a shop may be dependent upon a secondary shop for support, e.g., flight line team performs maintenance by replacement of a black box, and the faulty black box is repaired by a maintenance shop team. The personnel are assigned to either location, dependent on skill capabilities.

Consider a subsystem having a failure rate of .1 per hour (λ=.1), and a repair rate of 1 per hour in flight line maintenance (μ_1=1), and a repair rate of .5 per hour in the maintenance shop (μ_2=.5). There are 25 operational aircraft, which means that at most 25 subsystems could be operated simultaneously (N=25).

It is desired to determine what combinations of flight line maintenance teams and maintenance shop repair channels will satisfy the requirement that the mean number operable will be 18, (N_0=18).

Approach

A general approach which is applicable to multi-echelon support systems is to use a probabilistic activity network to estimate the service time. This method permits accounting for travel, time to acquire test equipment, and logistic waits. (See paragraph 9.3 for an application of this technique).

The following three approximation techniques may be used, and depending on circumstances, one will usually be a better fit than the others to actual maintenance policy.

a. Assume the maintenance shops contribute independently to down subsystems. Since the number of down units will be the sum of the down contributions for the flight line teams and the maintenance shop repair teams, any combination of $D_1+D_2<D-N_0$ will satisfy the system requirement. This approach is satisfactory when $N_0>>D_1+D_2$.

b. Based on N, determine the average wait for the black box repair cycle. Adjust, accordingly, the amount of time the flight line team spends to replace the black box. This approach will, in general, provide a good estimator of system behavior, presuming the flight line team stays with one subsystem until restored to operation.

c. Assume that the effect of the second level of maintenance is to reduce the number of operable subsystems which the flight line maintenance teams will service. The initial computation is made ignoring the flight line maintenance teams. Adjust the maximum number of units the flight line teams will be required to support. Calculate the number of units down, based on this adjustment.

Each of the approaches may be extended to include the cost optimization procedure.

It is of interest to note that although the assumptions vary widely for the specific approaches, the results are quite similar.

Approach 1 (Independent Shops)

Let:

$N=25$ $\quad N_0=18$ $\quad \mu_1=1.0$ $\quad \mu_2=.5$ $\quad \lambda=.1$

then

$P_1=.1$ $\quad P_2=.2$ $\quad D=dN$ $\quad s=0,$

The following tables are derived:

C_1=Flight line teams

C_1	2	3	4	5	6
D_1	6.15	3.10	2.45	2.33	2.28

C_2=Maintenance shop channels

C_2	4	5	6	7	8
D_2	6.60	5.03	4.45	4.25	4.20

The combinations of $D_1+D_2 < N-N_0$ providing feasible solutions to meet the operational requirements are

C_1	C_2
4 or more	6 or more

If a cost difference exists between flight line and maintenance repair teams, the election should be based on:

$$\text{Min } [a=a_1C_1+a_2C_2]; \; D_1+D_2 \leq N-N_0, \qquad \text{(III-36)}$$

where a_1 and a_2 are the cost of a flight line and maintenance repair team, respectively.

Approach 2 (Changing F)

In this approach, the waiting time by the flight line teams to acquire an operable black box from the maintenance shop is first computed. Using tables (N=25) and (P_2=.20000), the following values can be read off for (n_d), and the rest of the entries are derived from (n_d).

C_2	4	5	6	7	8
$n_{d,2}$	.264	.201	.178	.170	.168
$N_{d,2}$	6.60	5.02	4.45	4.25	4.20
$C_{b,2}$	3.68	4.00	4.11	4.15	4.16
$t_{w,2}$	1.59	0.51	0.17	0.05	0.02
$t_{ws,2}$	3.59	2.51	2.17	2.05	2.02

The value of μ_1 is adjusted (μ'_1) to compensate for $t_{s,s,2}$

$$t_1=1/\mu_1, \qquad \text{(III-37)}$$

$$t'=t_1+t_{s,s,2}, \qquad \text{(III-38)}$$

$$\mu_1'=1/t', \text{ and} \qquad \text{(III-39)}$$

$$P_1'=\lambda/\mu_1'. \qquad \text{(III-40)}$$

The (d), obtained by looking in the tables under (N-25) and (P=P1'), represents the total unreadiness of the flight line teams and the maintenance shop teams.

The results are tabled below in terms of (C_1), (C_2), (P_1'), and D=≤7.

	C_2	4	5	6
	P_1'	approx. 0.26	approx 15	approx 0..12
C_1	3		6.37	4.22
	4	9.85	4.18	3.04
	5	7.30	3.53	2.78
	6	7.00	3.29	2.70
	7	5.48	3.27	2.70

Summarizing,

C_1	C_2
3 or more	5 or more
6 or more	4 or more

Approach 3 (Changing N)

The approach of units awaiting or undergoing service (n_d) in the maintenance repair shop is calculated as in approach 1 (since s=0, n_d=d). The units used (N_1) for calculations involving the flight line are as follows:

N_1 *$=N_{o,2}$, and (III-41)

$N_{o,2}=N-D_2$. (III-42)

$P=.1$ $\lambda/\mu = 0,2$ $N_{o,1}=\min 18$

C_2		4	5	6	7	8
$N_{o,2}$		18.40	19.97	20.55	20.75	20.80
C_1	2	14.55	16.42	16.83	16.93	16.95
	3	16.52	17.85	18.33	18.49	18.53
	4	16.69	18.09	18.62	18.68	18.72
	5	16.73	18.15	18.68	18.76	18.82

Summarizing,

C_1	C_2
3	6 or more
4 or more	5 or more

8. Dimensional Analysis and Sensitivity Analysis

Application of any analytical routine is dependent upon maintaining a consistent dimensional system. The routine described in this section assumes consistent dimensions in all parameters. Some parameter inputs, however, are normally obtained in dimensional units which require conversion to be consistent in the system. Failure rates, for instance, are usually obtained in units of failures per operational hour, and service rates in terms of repairs per maintenance hour. These dimensions are not consistent unless the operational schedule conforms precisely to the maintenance schedule. To eliminate the problem of inconsistent dimensions, failure and repair rates should be converted to a time basis which has common definition.

For instance, if operational and maintenance schedules are expressed in terms of a repetitive week, the weekly time basis should be used as follows:

*Alternatively, $N_2=N_{o,1}=N-D_1$ may be used for the effective number of working units seen by the maintenance repair shop; either solution will satisfy requirements.

Let

λ_{hr} = failure rate /operational hour for one operational unit, and

λ_{wk} = failure rate/operational week = failure/rate/ maintenance week.

$\lambda_{wk} = h_{op} \lambda_{hr}$,

where

h_{op} = operational hours/week.

Let

μ_{hr} = service rate/maintenance hour,

μ_{wk} = service rate/maintenance week,

= service rate/operational week, and

$\lambda_{wk} = h_{mte} \mu_{hr}$,

where

h_{mte} = maintenance hours per week,

and

$p \;\; = \lambda_{wk} / \mu_{wk}$.

If more than one maintenance location is involved, with different work schedules, a service rate (μ) will be computed for each, contributing to different utilization factors.

As an example, consider an organization with the following characteristics:

λ_{hr} = 0.5 per operational unit,

μ_{hr} (organization) = 1.0,

λ_{hr} (field shop) = 0.5,

Operational schedule = 4 hours/day, 7 days/week,

Organizational maintenance schedule = 8 hours/day, 7 days/week.

Field maintenance schedule = 16 hours/day,
5 days/week.

Then

$$\lambda_{wk} = (28)(0.5) = 14, \quad \text{(III-44)}$$

$$\mu_{wk} \text{ (organization)} = (56)(1.0) = 56, \quad \text{(III-45)}$$

$$\mu_{wk} \text{ (field)} = (80)(0.5) = 40, \quad \text{(III-46)}$$

and

$$P_{org} = \lambda_{wk}/\mu_{wk} \text{ (organization)} = 0.25, \text{ and} \quad \text{(III-47)}$$

$$P_{fld} = \lambda_{wk}/\mu_{wk} \text{ (field)} = 0.35. \quad \text{(III-48)}$$

8.1 Preventive Maintenance

Preventive maintenance (PM) requirements are accommodated in either of two ways, depending upon whether preventive maintenance forms part of the primary workload or is a secondary workload. A guideline for this determination is the level of priority for scheduling preventive maintenance. If it can pre-empt a corrective repair, it is primary workload, but if PM is performed only when operational units, personnel, and facilities are uncommitted to corrective tasks, it is secondary.

In most cases, PM is considered secondary workload, and it is only necessary to determine whether sufficient unutilized time is available for its accomplishment.

The number of service channels available for secondary workload is $C-C_b$, where C is the number of channels assigned and C_b the mean number of busy channels. The time available for secondary workload is called "idle time" with respect to primary workload, and is

$$IT = h_{sto}(C-C_b). \quad \text{(III-49)}$$

It is required to determine whether preventive maintenance (and other secondary workload) is less than the time available for secondary workload. The same procedure is used to determine the capacity for other secondary workload. It should be noted that usual levels of operational readiness achievement require idle time with respect to primary workload. Utilization of this time for secondary workload is free. That is, within the limits of idle time availability, secondary workload can

be added at no additional cost for personnel and facilities, and often for repair equipment. For this reason, it is often feasible to incorporate at no cost such secondary workload as module repair, at a forward shop where this is not part of the primary workload.

If insufficient idle time is available, it is necessary to increase the number of personnel assigned. Depending upon the magnitude of necessary increase, this can be accomplished by adding channels, by adding a channel on one shift of a multi-shift schedule, or by increasing service channel team size. In any case, the modification may provide opportunity to reduce spares, while maintaining the required operational readiness level. If PM is considered part of the primary workload, its utilization factor (P) is added to that for corrective maintenance, in consistent dimensions, as described in preceding paragraphs on dimensional analysis.

Errors

Estimation of failure rates and services rates is subject to some degree of error, particularly when the equipment has not been built, or even completely designed. Use of the manning tables can determine the significance of the estimated parameter error. In many cases, errors are compensating, and in others, otherwise significant errors are rendered innocuous by virtue of the effect of asymptotic relationships.

An error in failure rate (λ) has the same effect as an error in operation rate (schedule), and an error in service rate has the same effect as an error in maintenance schedule. The effect is a change in the value of utilization factor (P), realizing that it is the ratio λ/μ in which error is significant, since $P=\lambda/\mu$ is the demand factor determining manning requirements. An error in estimating skill requirements for a task can result in an error in service rate, or in pipeline personnel.

The recommended means of determining the effect of expected error is to compare unreadiness values at reasonable error limits, and consider the advisability of modifying manning assignments to reduce the effect on unreadiness. Following is a list of error sources and effects on manning.

Parameter	
(λ) Failure Rate. Operating Schedule.	Affect Utilization Factor (P).
(μ) Service Rate. Maintenance Schedule. Skill Level Requirements.	
(P) Utilization Factor.	Affects Unreadiness (d), Service Channel, and Spares Requirements.
Skill Level Requirements	Affect Pipeline Personnel.

P_j, l_j personnel turnover rates.

9. Workload Determination

The foundation for the prediction of personnel requirements lies in the hardware and its demands for and application of manning and skills. The initial step in establishing manning and skill requirements is the determination of the relationship between performance/capability requirements and the equipment's reliability/maintainability characteristics, and the work created by the relationship. This provides the basis for establishment of repair channels in terms of skill teams or work shops. Failure rates (λ's) and service rates (μ's) for the equipment are developed by means of existing reputable reliability and maintainability prediction techniques.

Having established tasks that will occur, it is necessary to package these tasks for assignment to repair channels. The task responsibilities of a repair channel are called a "skill package." The skill package is identified with a repair channel type and with a personnel subsystem. The total maintenance personnel system is composed of personnel subsystems, each associated with a subsystem skill package of the system. The behavior of the personnel subsystem is described by an activity model. This activity model is describod by a finite cyclical queuing process.

9.1 Performance Requirements

During each working shift, the system must be capable of performing its prescribed function, or operation, for a specified duration and/or frequency.

Weighting frequency with the duration of each occurrence gives rise to a total operational capability during each shift. This requirement may take the more precise form:

a. Operating time per unit calendar time of which the operational unit should be capable.

b. Number of operations per unit calendar time of which the operational unit should be capable, and duration of performance per operation.

In establishing operational capability, it is desirable to differentiate between maximum, average and required performance capability.

a. Maximum operational requirements are difficult (if possible at all) to specify quantitatively.

b. Average performance requirements are those that can be expected in a quiescent state in the usage the system experiences as the result of either training personnel or equipment exercising. Average performance may be considerably less than performance capability required.

It is important to note not only the relationships among parameters, but also the effects of parameter variation. A change in failure rate (λ), or repair rate (μ), for example, can result in a change in the achieved value of operational readiness, or personnel and spares requirements, with a concomitant change in system support cost. In view of these relationships, manning is an optimization, based upon "skill packaging" tasks. It is significant that an error in estimating the skill requirements for a task package results simply in an error in the repair time.

9.2 Tasks Identified with System Functions

A system function may be defined as the level of equipment definition for which it is possible to specify a distribution of skills. A system function is identified with equipment. Each equipment is characterized by demand rates for maintenance support. Consider the following function breakout of an aircraft.

The aircraft (operational unit) is itemized in terms of fundamental functions, e.g.,

Fire Control	Air Frame System
Propulsion System	Communications
Armament System	Navigation
Pilot System	Hydraulic
Landing System	Safety (e.g., fire extinguishers, de-icers, ejection systems)

Determination of Tasks

The fundamental building block of the manning technique is the task. Ideally, the task is identified with a black box in the operational unit. The operational unit is comprised of a fixed number of black boxes.

For the purpose of analysis, the task is defined as a black box having the following demand rates:

a. Occurrence demand rate measured by failure rate, and

b. Performance demand rate.

For each demand occurrence, there is associated a duration of performance. This performance will require a number of personnel of a specific skill type and level. In the establishment of performance rates, it is assumed that a rate will depend on a task, and on the skill level performing the task. Random processes are assumed and mean rates are estimated, based on exponential processes.

Each combination of occurrence rate and task performance duration may have different skills and numbers of personnel required.

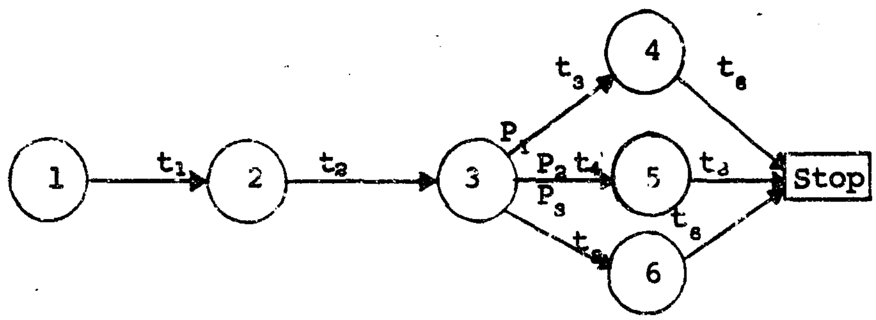
In summary, the black box task concept amounts to dividing maintenance requirements of the operational unit into reasonable work units or task packages. A "reasonable" work unit may consist of things to be done on the same occasion, but which are not conveniently performed simultaneously by different people. These things-to-be-done (tasks) will require the same skill field. The work may require primarily high skill, with a few low skill elements but, typically, not the converse, since the latter would lead to inefficient utilization of highly skilled personnel. The exception will arise when the workload

leads to requirements for only one or two men in a particular field, at a particular location. There will be borderline situations where there is some question as to whether a particular group of actions should be considered as one, or as more than one task. Little time should be spent in making such decisions, since they will almost never make a significant difference to the final result. In practice, the actions will generally be assigned to the same team, even when they are considered to constitute several tasks.

9.3 Activity Network for a Simplified Aircraft Function.

Consider a fire control subsystem comprised of an electronics black box. Electronic repair is performed by removing the black box on the flight line and replacing it with a spare, if available. The faulty black box is repaired at the field shop. The activity network for removal and replacement of the black box is constructed to depict the activities and events of the action.

The spare or replacement black box may be obtained through one of several routes. These routes and their characteristics form the basis for the network:



Activity characteristics are noted on interconnecting lines between circled numbers representing events.

The estimated values for these activities are:

Activity	Estimated Values
t_1=travel to maintenance shop	.3 hours
t_2=place faulty box in repair line	.2 hours
t_3=take box from ready inventory	.1 hours
t_4=await repair	1.5 hours
t_5=obtain box from base inventory	4.0 hours

t_6=return to aircraft .35 hours

p_1=probability of occurrence of t_3 .35

p_2=probability of occurrence of t_4 .60

p_3=probability of occurrence of t_5 .05

The expected time duration spent in acquiring the black box is:

$$E_{bb}=t_1+t_2+p_1t_3+p_2t_4+p_3t_5+t_6 \qquad \text{(III-50)}$$

$$\approx 2.0 \text{ hours.}$$

9.4 Tradeoff of Spares at Different Assembly Levels

Consider a squadron of 20 aircraft (M=20). The return in operational readiness from an additional spare black box (ΔR_s) is 0.0005, and the cost of the spare is $8000. Alternatively, an additional aircraft can be acquired, decreasing unit aircraft readiness from 0.750 to 0.745 with no change in support facilities or personnel.

The return in capability per unit cost of the spare black box is

$$r_s=m''R_s/C_s=20X0..0005\&8000+1.25X10^{-6}. \qquad \text{(III-51)}$$

For an additional aircraft, the unit return is

$$r_a[(m+r)R_a-mR_b]/C_a=[(21)0.745-(20)0.750]/500,000$$

$$=1.29X10^{-6}. \qquad \text{(III-52)}$$

Obviously, the rate of return in capability for the additional aircraft is greater per unit cost than for the spare black box indicating preference for an additional aircraft. Conversely, an aircraft is less costly per unit return in readiness.

9.5 Interpolation Techniques for Subassembly Sparing

Suppose the skill package consists of

(l) repairable assemblies (modules)

(m) assemblies requiring piece part repair, and

(n) off line preventive maintenance actions

The contributions to the utilization factor will

$$P_1=\sum_{i=1}^{i}P_{1i}=\sum_{i=1}^{i}(\lambda_i/\mu_i) \qquad \text{(III-53)}$$

$$P_2=\sum_{j=1}^{n}P_{2j}=\sum_{j=1}^{n}(\lambda_k/\mu_j) \qquad \text{(III-54)}$$

$$P_3=\sum_{k=1}^{n}P_{3k}=\sum_{k=1}^{n}(\lambda_k/\mu_k) \qquad \text{(III-55)}$$

The utilization factor for the skill package will be

$$P_t=P_1+P_2+P_3 \qquad \text{(III-56)}$$

Since the repairable assemblies make unequal contributions to the utilization factor and can differ in cost, it is required that a method be established to choose between assemblies.

The change in unreadiness between having no spare and one skill package spare is

$$\Delta d_1=(d_0-d_1) \qquad \text{(III-57)}$$

Since only (P_1) portion of the utilization factor is supported by spare repairable assemblies (assuming part spare availability) unreadiness can be affected by providing spares associated with this aspect of the work load only.

Suppose there is only one spareable assembly in the skill package. The effect on unreadiness as additional spares are allocated is illustrated below.

Spares	Unreadiness Change	Unreadiness	
1	$\Delta d_1=(d_0-d_1)P_1/P_t$	$d_0-(d_0-d_1)P_1/P_t$	(III-58)
2	$\Delta d_2=(d_1-d_2)P_1/P_t$	$d_0-(d_0-d_2)P_1/P_t$	(III-59)
i	$\Delta d_i=(d_{i-1}-d_i)(P_1/P_t)$	$d_0-(d_0-d_i)P_1/P_t$	(III-60)

Where the skill/hardware package is comprised of more than one spareable assembly, the multinomial probability distribution is used for interpolation:

If the distribution of spare assemblies is

$$s_1, s_2, s_3, \ldots, s_n,$$

the maximum demand for spares that could be satisfied is

$$n = s_1 + s_2 + s_3 + \ldots + s_n. \qquad \text{(III-61)}$$

There is a probability of satisfying any demand

$$n-1,\ i=o,\ 1,\ 2,\ \ldots n,$$

a fraction of the time. In order to interpolate, it is required to determine the probability of satisfying a demand for (n-1) spares, (i=o, 1, ...n) given that the demand occurs. Thus, if (n_{dj}) is the number of ways in which the demand for (n-i=j) spares can result from different subassembly demands, and (n_{sj}) is the number of ways in which the distribution of spares $(s_1, \ldots, s_n)$ can satisfy that demand, then the fraction of time that the distribution of assembly spares will be equivalent to the same number of skill package/hardware spares is

$$D_j = \frac{N_{sj}}{N_{dj}} \qquad \text{(III-62)}$$

The unreadiness of the hardware or skill package as a result of a distribution of spare assemblies is as follows:

For a spare assembly complement

$$s_1, s_2, s_3, \ldots s_i, \ldots s_n$$

let a minimum (s_i) be (m)

$$d = d(m) - \sum_{m}^{n-1} (d_j - d_{j+1}) D_{j+1} \qquad \text{(III-63)}$$

The table below illustrates for the case of two types of assemblies, the unreadiness as a function of various combinations of assembly spares.

	Assembly Type 1	Assembly Type 2	Unreadiness
	0	0	d_0
Spares	1	0	$d_0-(d_0-d_1)P_{11}$*
	2	0	$d_0-(d_0-d_2)P_{11}$
	1	1	$d_1-(d_1-d_2)2P_{11}P_{12}$
	2	1	$d_1-(d_1-d_2)(P^2_{11}+2P_{11}P_{12})$
	2	2	$d_2-(d_2-d_3)(3P^2_{11}P_{12}+3P_{11}P^2_{12})$ $-(d_3-d_4)(6P^2_{11}P^2_{12})$

$$*P_{11}=P_1/P_1+P_2,\ P_{12}=P_1/P_1+P_2 \qquad \text{(III-64)}$$

Tables III-3 and III-4 illustrate two specific cases, for three assembly types, and for (n) types.

SPARES INTERPOLATION - THREE ASSEMBLY TYPES

TABLE III-3

SPARES

ASSEMBLY TYPE 1	2	3	UNREADINESS (d)
0	0	0	d_0
1	0	0	$d_0-(d_0-d_1)P_{11}$*
1	1	0	$d_0-(d_0-d_1)P_{11}+P_{12}-(d_1-d_2)2P_{11}P_{12}$
1	1	1	$d_1-(d_1-d_2)(2P_{11}P_{12}+2P_{11}P_{13}$ $+2P_{12}P_{13})-(d_2-d_3)6P_{11}P_{12}P_{13}$
2	0	0	$d_0-(d_0-d_2)P_{11}$
2	1	1	$d_1-(d_1-d_2)(P^2_{11}+2P_{11}P_{12}+2P_{12}P_{13}$ $+2P_{11}P_{13})-(d_2-d_3)(3P^2_{11}P_{12}$ $+3P^2_{11}P_{13}+6P_{11}P_{12}P_{13})$ $-(d_3-d_4)12P^2_{11}P_{12}P_{13}$
2	2	0	$d_0-(d_0-d_2)(P_{11}+P_{12})$ $-(d_2-d_3)(3P^2_{11}P_{12}+3P_{11}P^2_{12})$ $-(d_3-d_4)6P^2_{11}P^2_{12}$
2	2	1	$d_1-(d_1-d_2)P_{11}+P_{12}$ $-(d_2-d_3)(3P^2_{11}P_{12}+3P^2_{11}P_{13}$ $+3P_{11}P^2_{12}+3P^2_{12}P_{13}+6P_{11}P_{12}P_{13})$ $-(d_3-d_4)(6P^2_{11}P^2_{12}+12P^2_{12}P_{11}P_{13}$ $+12P_{11}P^2_{12}P_{13})-(d_4-d_5)30P^2_{11}P^2_{12}P_{13}$

*See NOTE on Table III-4.

SPARES INTERPOLATION - N ASSEMBLY TYPES

TABLE III-4

	ASSEMBLY TYPES	UNREADINESS (d)
	1 2 3 ... g h ... n	
	0 0 0 ... 0 0 ... 0	d_0
	1 0 0 ... 0 0 ... 0	$d_0-(d_0-d_1)P_{11}$
SPARES	1 1 1 ... 1 0 ... 0	$d_0-(d_0-d_1)\sum_{i=1}^{g} P_{1i}$
		$-(d_1-d_2)\left(\sum_{i=1}^{g}\sum_{k=1}^{g} P_{1i}P_{1k}\right)$, $i \neq k$
		$-(d_2-d_3)\left(\sum_{i=1}^{g}\sum_{k=1}^{g}\sum_{m=1}^{g} P_{1i}P_{1k}P_{1m}\right)$
		$- \cdots$
		$\cdots$
		$\cdots$
		$-(d_{g-1}-d_g)\left(\sum_{i=1}^{g}\cdots\sum_{l=1}^{g}P_{1i}\cdots P_{1l}\right)$

NOTE: $P_{1i}=P_i/\sum_{i}^{n}P_i=P_i/P_t$ (III-65)

Additional Concepts on Subassembly Sparing

1. If the subsystem consists of (n) identical subassemblies, each with failure rate (λ) and service rate (μ), the aggregate failure rate is ($n\lambda$), and

$$P = n\lambda/\mu \qquad \text{(III-66)}$$

where (P) is the utilization factor. A spare consists of one subassembly.

2. If (m) of (n) identical subassemblies are redundant and inactive, then aggregate failure rate is [$(n-m)\lambda$], and

$$P = (n-m)\lambda/\mu \qquad \text{(III-67)}$$

A spare consists of one subassembly, with (m) spares already assigned.

3. If (m) of (n) identical subassemblies are actively redundant, the aggregate failure rate is ($n\lambda$), and

$$P = n\lambda/\mu \qquad \text{(III-68)}$$

A spare consists of one subassembly, with (m) spares already assigned.

4. If the subsystem consists of (n) subassembly types, and (m_i) subassemblies of type (i),

$$\sum_{1}^{n} m_i \lambda_i = \text{aggregate failure rate} \qquad \text{(III-69)}$$

$$P = \sum_{1}^{n} m_i \lambda/\mu_i$$

The interpolation technique described preceding is required to determine the optimal spares mix.

Comment on Optimization

The rate of change in unreadiness depends, of course, upon the distribution of assembly spares. The optimum mix is that providing the greatest return in readiness per unit resource cost. Optimization is practically accomplished by selecting spares increments based upon marginal return in readiness per unit of resource cost.

The distribution of assemblies for assignment of the first spare is determined from the ranking of normalized utilization factors (P_{ij}). Assignment of a second spare depends upon the contribution of the second power of the appropriate normalized utilization factor being greater than that of the normalized utilization factor of the alternate candidate for a first spare. ($P^2_{ij}\Delta d_2 > P_{ik}\Delta d_1$). Subsequent spares are assigned similarly.

TABLES

(SAMPLES)

N= 9 P= .35000

TABLES

(SAMPLES)

S \ C	3	4	5	6	7
0	.302 .302	.268 .268	.261 .261	.259 .259	
1	.247 .316	.196 .273	.185 .261	.182 .258	
2	.206 .334	.140 .275	.121 .259	.116 .254	
3	.178 .349	.100 .276	.075 .253	.068 .247	.066 .246
4	.157 .363	.073 .275	.049 .246	.036 .237	.034 .235
5	.142 .376	.054 .272	.028 .237	.019 .226	.016 .223
6	.129 .389	.041 .266	.017 .227	.010 .214	.007 .210
7	.120 .400	.031 .263	.011 .216	.005 .202	.003 .198
8	.112 .410	.024 .257	.007 .206	.003 .192	.001 .187
9	.105 .420	.019 .250	.004 .197	.001 .181	
10	.099 .430	.014 .243	.003 .188	.001 .172	
11	.094 .438	.011 .236	.002 .179		
12	.090 .447	.009 .229	.001 .171		
13	.086 .455	.007 .222	.001 .164		
14	.083 .463	.005 .215			
15	.080 .470	.004 .209			
16	.078 .477	.003 .202			
17	.076 .484	.003 .196			

N= 10 P= .35000

S \ C	3	4	5	6	7	8
0	.319	.274	.262	.260		
	.319	.274	.262	.260		
1	.275	.212	.194	.189		
	.339	.281	.264	.259		
2	.243	.161	.135	.128	.126	
	.359	.287	.263	.257	.255	
3	.221	.124	.090	.079	.077	
	.380	.292	.261	.252	.249	
4	.205	.098	.059	.046	.043	
	.399	.295	.257	.244	.241	
5	.193	.079	.040	.026	.022	.021
	.418	.297	.251	.235	.230	.229
6	.184	.064	.027	.015	.011	.009
	.437	.298	.243	.225	.219	.217
7	.177	.053	.019	.009	.005	.004
	.454	.298	.235	.215	.208	.206
8	.171	.045	.013	.005	.003	
	.471	.297	.227	.205	.197	
9	.166	.038	.009	.003	.001	
	.487	.295	.219	.195	.188	
10	.162	.032	.006	.002	.001	
	.502	.293	.211	.186	.178	
11	.159	.027	.004	.001		
	.517	.290	.203	.178		
12	.157	.023	.003	.001		
	.531	.286	.195	.170		
13	.155	.020	.002			
	.545	.282	.187			
14	.153	.017	.001			
	.558	.278	.180			
15	.151	.015	.001			
	.570	.274	.174			
16	.150	.013	.001			
	.582	.269	.167			
17	.149	.011	.001			
	.594	.263	.161			

№ 29 Pe ,10000

S	C 2	3	4	5	6
0	,246 ,246	,124 ,124	,098 ,098	,093 ,093	,091 ,091
1	,235 ,264	,076 ,128	,067 ,099	,060 ,093	,058 ,091
2	,227 ,282	,074 ,132	,042 ,100	,034 ,092	,033 ,090
3	,221 ,300	,058 ,136	,026 ,099	,018 ,091	,016 ,089
4	,217 ,318	,046 ,139	,016 ,098	,009 ,089	,007 ,086
5	,213 ,335	,037 ,141	,010 ,097	,004 ,087	,003 ,084
6	,210 ,352	,030 ,143	,006 ,095	,002 ,084	
7	,208 ,369	,024 ,144	,004 ,093	,001 ,082	
8	,2[illegible]7 ,385	,020 ,144	,002 ,091	,001 ,080	
9	,205 ,401	,016 ,144	,001 ,088		
10	,204 ,416	,013 ,144	,001 ,086		
11	,203 ,430	,011 ,143	,001 ,084		
12	,203 ,444	,009 ,142			
13	,202 ,458	,008 ,141			
14	,202 ,471	,006 ,139			
15	,201 ,483	,005 ,138			
16	,201 ,495	,004 ,136			
17	,201 ,506	,004 ,134			

N= 25 P= ,20000

S	C 4	5	6	7	8	9
0	,264	,201	,178	,170	,168	
	,264	,201	,178	,170	,168	
1	,250	,176	,148	,138	,135	,134
	,279	,208	,181	,171	,168	,167
2	,239	,153	,120	,108	,104	,102
	,294	,215	,183	,172	,168	,167
3	,230	,134	,095	,081	,076	,074
	,310	,222	,186	,173	,168	,166
4	,223	,118	,074	,058	,052	,050
	,326	,230	,188	,173	,167	,165
5	,218	,106	,05[illegible]	,041	,034	,031
	,342	,237	,190	,172	,165	,163
6	,214	,096	,046	,028	,021	,019
	,358	,24[illegible]	,191	,171	,163	,160
7	,211	,087	,037	,020	,013	,011
	,374	,251	,192	,169	,160	,157
8	,20[illegible]	,080	,030	,014	,008	,006
	,389	,258	,192	,166	,156	,153
9	,207	,074	,024	,010	,005	,003
	,404	,265	,192	,163	,153	,148
10	,206	,069	,020	,007	,003	,002
	,418	,271	,191	,160	,149	,145
11	,204	,065	,016	,005	,002	
	,432	,277	,189	,157	,146	
12	,204	,061	,013	,004	,001	
	,446	,282	,188	,154	,142	
13	,203	,057	,011	,003	,001	
	,459	,288	,186	,151	,138	
14	,202	,054	,009	,002		
	,472	,293	,184	,147		
15	,202	,051	,008	,001		
	,484	,298	,182	,144		
16	,201	,049	,006	,001		
	,496	,303	,179	,141		
17	,201	,047	,005	,001		
	,507	,307	,177	,138		
18	,201	,045	,004			
	,518	,311	,174			
19	,201	,043	,004			
	,5[illegible]	,315	,172			
20	,201	,041	,003			
	,539	,319	,169			

APPENDIX IV

SKILL SENSITIVITY TABLES

1. INTRODUCTION

A multitude of factors are directly or indirectly related to system manning requirements. An analysis of the significant factors has been made and the results appear in tables IV-1 and IV-2. For these tables, the description of each factor includes its identity and the measurements of primary concern to manning. Each factor is mated with its relationship to personnel in a system. The measures are given below the identification of the factor. The personnel are classed in either maintenance or operation categories. Relations given in the tables represent rough-cut effects of a change in the factor as reflected in changed manning requirements.

Factors have been selected according to their potential importance. In particular situations, any factor may loom larger than others. The magnitude of effect of a particular factor depends on the magnitude of its change.

Ease of estimation of the effects of a factor is closely related to the basic ease of measurement of the factor itself. However, in most cases, the uncertainty of an estimate stems more from the uncertainty of input data to the estimating process than from errors in the estimating process itself. Uncertainty of input is inevitable. By using these factors as guides, the degree of uncertainty is minimized through clear establishment of the type of input data that is needed. Here, the benefit lies in assuring that valuable data which are attainable will be made available.

Factors in the tables may be classified both according to their association with the equipment, and to their effects on the manning requirements of the system. Table IV-1 contains factors relating to hardware and its applications. Table IV-2 contains factors relating to support equipment and organization. Some factors affect primarily the man-hours of actual labor required, while others affect primarily the efficiency with which men can be used - the fraction of the time they are working productively.

2. CONDITIONS OF APPLICABILITY

The applicability of tables IV-1 and IV-2 is limited as follows:

a. Relationships provide appropriate approximations whereever new systems of equipments can be viewed as consisting of hardware similar in type to that of existing systems or equipment. The accuracy of the estimate will depend, in part, upon the degree of similarity. For example, application of relationships to maintenance manning requirements on inertial navigation equipment are appropriate, using other inertial navigation equipment as a basis for comparison, but not using stellar navigation equipment. Note, however, that computer subsystems in both systems might be appropriately compared.

b. The consequences of queuing (random workload requirements) must be considered as modifying all effects in the tables. Queuing effects are discussed in appendices III and VI.

c. Manning adjustments should always be based upon personnel skill specialty codes, since reductions or increases in manning are directly related to reductions or increases in specific skill hours of work available.

3. GENERAL CONTENTS

In table IV-1, the specific factors can be categorized as follows:

1 to 6 - Characteristics appropriate to estimation of requirements for skill and man-hours of actual labor. Apply at all levels.

7 to 9 - As applied to hardware, same as 1 to 6. As applied to personnel, characteristics of the utilization of the hardware which affect the accomplishments possible by a man in a given time.

10 to 11 - Characteristics of the system at the equipment level which affect the requirements for actual (skill) man-hours of labor.

12 to 13 - Characteristics of the organization using the equipment, which affect the efficiency with which men can be used (i.e., proportion of time which men are not "idle" with respect to their duties associated with their primary AFSC).

14 to 15 - Characteristics of the use of the equipment which affect the efficiency with which men can be used.

For table IV-2, the factors may be categorized as:

1 - Characteristics of maintenance equipment affecting skill and man-hours of effort required to maintain the operating and maintenance equipment.

2 - Characteristics of organization for maintenance which affect the efficiency with which men can be used.

3 to 5 - Characteristics of organization for maintenance and logistics which affect equipment downtime for repair. Manning often may be traded off with these characteristics in order to achieve a specified operational readiness.

The factors which affect the amount of actual man-hours of labor required can be dealt with directly. Those affecting "idle" time require dealing with the interrelations of various factors which are involved in queuing problems.

TABLE IV-1

EFFECT ON MANNING AND SKILL REQUIREMENTS OF FACTORS IN DESIGN AND OPERATION OF EQUIPMENT

	Factor	Measurement	Effect on Personnel Requirements
1.	Number of similar items	Count	Maintenance- On manning proportional. Operation- Proportional to negligible.
2.	Size	Weight, volume	Maintenance and Operation - Negligible. Within an order of magnitude, size per se generally has relatively little effect on manning, except where heavy items must be man-handled, and where, in rare instances, tasks are dependent on size, as in cleaning (important for high speed aircraft).
3.	Addition (or elimination) of a function, or change in means of performing an existing one: (a) new system or equipment; (b) existing equipment.	Type of hardware (electronic, mechanical...) (see also entries 4, 5, 8, 9 and 11 below.)	Maintenance- Changes relative to demand for different skills. (b) only - May increase demand for skills required for maintenance of items whose access is worsened by new addition.
4.	Maintainability	Mean-time-to-repair and skill level required.	Maintenance- On manning, proportional (as weighted by failure rate). Operation- Negligible.

2

TABLE IV-1 (CONT.)

EFFECT ON MANNING AND SKILL REQUIREMENTS OF FACTORS IN DESIGN AND OPERATION OF EQUIPMENT

	Factor	Measurement	Effect on Personnel Requirement
5.	Reliability	Failure rate including all part or adjustment failures.	Maintenance- On manning, proportional (as weighted by repair times).
6.	Average mission duration and frequency, or for items having continuous mission, the fraction of time at high stress.	Operating hours per hour and/or missions per hour, and proportion at each stress level (e.g., fraction of mission flown at supersonic speeds or with afterburner or fraction of time transmitter is on).	Maintenance- Manning is proportional to duration of stress applied to equipment during the mission. Operation- Manning is proportional to negligible, depending on initial efficiency in use of operators.
7.	Stress Severity	Temperature, (g)'s (shock and vibration) (e.g., supersonic vs. subsonic flight).	Maintenance- According to effect of stress on failure rate or on need for preventive maintenance. Operation- Negligible where stress is on equipment. Where stress is on operator, negligible to proportional depending upon the extent to which the operator's ability to withstand the stress is the limiting factor with respect to his workload.

2

TABLE IV-1 (CONT.)

EFFECT ON MANNING AND SKILL REQUIREMENTS OF FACTORS IN DESIGN AND OPERATION OF EQUIPMENT

	Factor	Measurement	Effect on Personnel Requirements
8.	Climate at site (if equipment is not in controlled environment).	Temperature, humidity, and wind profiles. Inches of rain, inches of snow.	Maintenance- Manning increases as extremes in environment increase on equipment and thus increase failure rate. Increases as environment increases time to repair exposed items. Operation- Increases as extremes in environment reduce working hours per day, per operator. Maintenance and Operation- Where climate regularly affects relevant travel time - fog, snow, muddy roads, etc. - appropriate adjustments are required. Overtime will generally compensate for occasional delays.
9.	Other environment factors such as dust, salt spray, insects, etc.	Effect on failure rate and/or working efficiency.	Maintenance and Operation- Increases failure rate and/or reduces repair rate according to severity (specific analysis is required).
10	Packaging	Number of levels of assembly which are plug-in.	Maintenance- Facilitates centralized repair of the lower levels of assembly, reducing manning, especially high skills. See also table 2, entry No. 4.

2

TABLE IV-1 (CONT.)

EFFECT ON MANNING AND SKILL REQUIREMENTS OF FACTORS IN DESIGN AND OPERATION OF EQUIPMENT

	Factor	Measurement	Effect on Personnel Requirements
11.	Automaticity (degree of).	Man-hours of effort performed by operator compared to those performed automatically; (i.e., the number of man-hours required if work were done manually instead), and/or men replaced by automatic features compared to men required and/or reduction in operator skills required. (Consider only tasks which could be performed either automatically or manually.	Maintenance- Increases skill level and manning. Operation-Reduces skill level and/or manning.
12.	Dispersion	Travel time between units by practical" means of transport of maintenance man, or failed and replacement items.	Maintenance- Manning increases with increased dispersion. Rate of increase decreases for higher echelons. Operation- Negligible
13.	Isolation	Travel time to nearest facilities which can be shared.	Maintenance- Manning increases to the point that shared facilities are not used. Operation- Negligible except as services can be shared (e.g., communications).

2

/

TABLE .V-1 (CONT.)

EFFECT ON MANNING AND SKILL REQUIREMENTS OF FACTORS IN DESIGN AND OPERATION OF EQUIPMENT

	Factor	Measurement	Effect on Personnel Requirements
14.	Uniformity of mission occurrences (applied primarily to aircraft flights - ground equipment generally has "continuous" mission as used here).	Ceofficient of variation[1] of number of missions per (t), where (t) is maintenance time per mission.	Maintenance and Operation- Manning decreases with increasing uniformity because workload is more uniform and men can be utilized more efficiently.
15.	Maximum Allowable Continuous Downtime and/or Operational Readiness	Time permitted	Maintenance- Manning increases as the limit on downtime is lowered or as operational readiness requirement is increased.

[1]Coefficient of variation (standard deviation/means) is inversely related to uniformity. For random occurrence (Poisson events), the value is 1. For bunching (e.g., flights of several aircraft on the same combat mission event), the value is greater than 1. For spacing (e.g., patrol flights by single aircraft), the value is less than 1.

2

TABLE IV-2

EFFECT ON MANNING AND SKILL REQUIREMENTS OF FACTORS IN EQUIPMENT AND ORGANIZATION FOR MAINTENANCE SUPPORT

	Factor	Measurement	
1.	Automatic checkout equipment (ACE) and special test equipment (STE).	Man-hours of effort performed by user compared to those eliminated by automatic features, and/or men replaced by automatic features compared to men required and/or reduction in operator skills required. (Consider only tasks which could be performed either automatically or manually.)	Maintenance- Proportionately reduces manning and skill required for direct maintenance. Increases demand for high skill required to maintain ACE and STE.
2.	Shift from local to centralized maintenance when, locally, there is: (a) low utilization, (b) moderate utilization, (c) high utilization.	Squadrons supported per shop.	Maintenance- a. Increases total manning slightly if local manning is not reduced. Decreases manning by large factor if local maintenance is reduced. b. Reduces manning when local manning is reduced appropriately. c. Little change if local manning is reduced appropriately. Operation- Negligible except as operator performs maintenance.

2

TABLE IV-2 (CONT.)

EFFECT ON MANNING AND SKILL REQUIREMENTS OF FACTORS IN EQUIPMENT AND ORGANIZATION FOR MAINTENANCE SUPPORT

	Factor	Measurement	Effect on Personnel Requirements
3.	Logistic delays.	Time between order and delivery.	Lessening of logistic efficiency implies lowering of operational readiness. Increases in manning necessary to compensate. Increase in skill also may lead to more use of non-standard fixes in emergencies.
4.	Highest level of assembly spared on site (for each part of equipment).	Mean-time-to-repair by replacing at that level of assembly.	Maintenance- Reduces on-site manning and, if these levels are repaired at higher echelons, often reduces skill requirements.
5.	On-site inventory of spare parts and assemblies.	Level of protection against shortage.	Maintenance- Lower level of protection implies lower operational readiness unless increased manning is used to compensate.

2

APPENDIX V

DETAILED PROCEDURE FOR

DESIGN/SUPPORT ALTERNATIVE ANALYSIS

1. GENERAL OPERATION AND SUPPORT RELATIONSHIP TO SYSTEM VALUE

Regardless of the set of mission requirements that is established for a system and transformed into performance parameters, when these parameter values are transformed into a proposed hardware configuration which meets the value requirements of the system, the task remains to determine how to get the most for our operation and support investment. What is desired to maximize for this investment is directed to the specific mission(s) which the system is to accomplish. In general, what will be required is achievement of operational readiness.

After defining a specific design alternative in terms of hardware/software, the next task is to evaluate the effect of the application upon cost and operational performance. First, it must be understood that the sole purpose of the operational/support system is to keep the system either operational or in a state of readiness. Thus, given a design alternative, the best method of support must be determined, considering the alternatives. To achieve this end will require evaluation of support alternatives. The evaluation of support alternatives consists of determining demonstrable differences in operating and maintenance personnel, quantities of spares, support equipment, etc. The support alternative selected in conjunction with each design alternative must permit meeting the operational readiness requirement in the least costly manner with that design alternative.

The significance of and necessity for this lies in the recognition that design alternatives should be evaluated in terms of total expected costs established under unbiased conditions. A good design alternative can be made to look bad from the cost point of view, if the design of the support alternative will result in a high cost support structure. The analysis required to establish the least total expected cost based on the operational environment is amenable to incremental analysis, using total expected cost differences. The procedure which follows is based on the three-echelon United States Air Force support system.

The principal problem in analysis of the support system is determining where something is to be done, if done at all. Generally, there will be considerable latitude in terms of design

alternatives, but this latitude will be constrained by already existing support facilities, skill capabilities, and operational requirements of the system. Given the preliminary operational and support structure constraints, a relatively simple elimination procedure can be employed for evaluation of alternatives. Table V-1 illustrates the range of alternatives for the support of a system consisting of three levels of assembly. For each level of assembly, a decision must be relative to two questions, (a) if that level of assembly fails, should it be repaired?, and (b) if it is repaired, where in the support system should it be repaired?

In establishing the answers to the questions above, it is desirable to perform no more computations than necessary. Table V-2 presents one such procedure. (Because of the possible differences associated with cost at the factory, and the relatively infrequent use of factory repair, costs at factory are not included in table V-2). The general rule for a decision, when using table V-2, is simply to choose the least costly alternative. That is, if

$$\Delta T_{j,i} < 0, \qquad \text{(V-1)}$$

choose alternative (j),

conversely, if

$$\Delta T_{j,i} > 0, \qquad \text{(V-2)}$$

choose alternative (i).

The procedure which follows is based on the availability of alternative design configurations, among which an optimum will exist. If the level of assembly configuration is fixed with respect to detail module design, the procedure simply determines where maintenance should be performed.

2. PROCEDURE

The step-by-step procedure is detailed below:

Step 1, Organization -

a. Select one higher modular assembly configuration (h).

b. Evaluate the cost of discard. (Use tabular form provided by figure 5, section 4.

TABLE V-1
POSSIBLE SUPPORT ALTERNATIVES

No.	Units Involved	Organization	Field	Depot	Factory
1	Organization	Part repair HMA*			
2		Discard Module			
3		Discard HMA			
4	Organization-Field	R and R Module	Discard Module		
5		R and R Module	Module repair		
6		R and R** HMA	Discard HMA		
7		R and R HMA	Discard Module		
8		R and R HMA	Part repair HMA		
9	Organization-Depot	R and R Module		Discard Module	
10		R and R Module		Module repair	
11		R and R HMA		Discard HMA	
12		R and R HMA		Discard Module	
13		R and R HMA		Part repair HMA	
14	Organization-Factory	R and R Module			Discard Module
15		R and R Module			Module repair
16		R and R HMA			Discard HMA
17		R and R HMA			Discard Module
18		R and R HMA			Part repair HMA
19	Organization-Field-Depot	R and R HMA	R and R Module	Discard Module	
20		R and R HMA	R and R Module	Module repair	
21	Organization-Field-Factory	R and R HMA	R and R Module		Discard Module
22		R and R HMA	R and R Module		Module repair
23	Organization-Depot-Factory	R and R HMA		R and R Module	Discard Module
24		R and R HMA		R and R Module	Module repair

*HMA = higher modular assembly
**R and R = remove and replace

TABLE V-2

TABULAR EVALUATION PROCEDURE

Echelon	Step	Organization		Field		Depot		T_i	Compare	Decision
		Rep.	Dis.	Rep.	Dis.	Rep.	Dis.			
Organization O_2	1	h*						T_2	T_2, T_1	$\Delta T_{2,1}>0$;choose T_1 $\Delta T_{2,1}<0$;choose T_2
O_1			h					T_1		
O_3	2	h	m**					T_3	$T_3, \min(T_2, T_1)$***	$\Delta T_{3,min}>0$;min $\Delta T_{3,min}<0;T_3$
O_4	3	h		m				T_4	$T_4, \min(T_3, T_2, T_1)$	$\Delta T_{4,min}>0$;min $\Delta T_{4,min}<0;T_4$
O_5	4	h				m		T_5	$T_5, \min(T_4, T_3, T_2, T_1)$	$\Delta T_{5,min}>0$;min $\Delta T_{5,min}<0;T_5$
Field F_2	5			h				T_7	T_7, T_6	$\Delta T_{7,6}>0:T_6$ $\Delta T_{7,6}<0;T_7$
F_1					h			T_6		
F_3	6			h	m			T_8	$T_8, \min(T_7, T_6)$	$\Delta T_{8,min}>0$;min $\Delta T_{8,min}<0;T_8$
F_4	7			h		m		T_9	$T_9, \min(T_8, T_7, T_6)$	$\Delta T_{9,min}>0$;min $\Delta T_{9,min}<0;T_9$
Depot D_2	8					h		T_{11}	T_{11}, T_{10}	$\Delta T_{11,10}>0;T_{10}$ $\Delta T_{11,10}<0;T_{11}$
D_1							h	T_{10}		
D_3	9					h	m	T_{12}	$T_{12}, \min(T_{12}, T_{11})$	$\Delta T_{12,min}>0$;min $\Delta T_{12,min}<0;T_{12}$
D vs. F	10			$\min(T_{12}, T_{11}, T_{10})$, $\min(T_9, T_8, T_7, T_6)$						$\Delta T_{D,F}>0;T_F$ $\Delta T_{D,F}<0;T_D$
min(D,F) vs. O	11	$\min(T_{12}, T_{11}, T_{10}, T_9, T_8, T_7, T_6)$, $\min(T_5, T_4, T_3, T_2, T_1)$								$\Delta T_{min,O}>0;O$ $\Delta T_{min,O}<0$ min

*h = Higher Modular Assembly
**m = Module
***$\min(T_2, T_1)$ = Least cost estimate between T_2 and T_1, etc.

c. Evaluate the cost of repair of the same assembly, considering that all lower levels are repaired, e.g., modules. (Use same tabular form as (b) above.

d. Compare (1c) with (1b) above.

e. Make a decision based on equations V-1 and V-2.

Step 2, Organization -

a. Select one of the possible module (m) configurations that is a potential candidate for discard-at-failure-maintenance (DAFM). The higher modular assembly is repaired by replacing DAFM modules.

b. Evaluate cost of policy described above.

c. Evaluate least cost result of step 1 again; remember that the things that are constant for step 1 (and cancelled out) will not necessarily be constant in the revised policy appropriate to step 2.

d. Make a decision based on equations V-1 and V-2.

Steps 3 and 4, Organization - These steps evaluate the same module repair at field and at depot. Higher modular assembly repair is performed at organization level with the repaired modules.

Steps 5, 6, and 7, Field - These steps evaluate the same higher modular assembly and the same module configuration, but bypass the organizational level. Step 5 repeats the detail of step 1, step 6 repeats the detail of step 2, etc.

Steps 8 and 9, Depot - These steps evaluate the same higher modular assembly and the same module configuration, but bypass the organizational and field levels. Step 8 repeats the details of step 1, and step 9 repeats the details of step 2.

Step 10, Depot vs. Field - This step evaluates the least cost estimate of depot policy against the least cost estimate for field acquisition and support policy.

Step 11, Minimum (Field, Depot) vs. Organization - This step evaluates the least cost estimate determined in step 10 against the least cost estimate of organization level.

Result - The result of this step-by-step procedure is the evaluation of a least cost estimate of acquisition, operation, and support for one higher modular assembly and one module configuration. Also, by using the tabular procedure, the location of the least cost level of maintenance is developed.

3. SUMMARY

By successive reapplication of the step procedure to different module configurations within the higher modular assembly chosen, (allocation of module functions), the least cost module is chosen for its allocated functions within the higher assembly. Then a different higher modular assembly is selected, functionally equal to the first, but with a different allocation of functions to module positions. The whole process is repeated. Table V-3 illustrates the refining process towards attaining a least cost situation involving higher modular assembly, module, and location of maintenance. The reapplication process can be carried out a step higher, when the problem is finding a least cost alternate design layout of higher modular assembly types and sizes within equipment, etc. There is no limit to the ideas involving size and type of modules, higher modular assembly, equipment, etc., except that imposed by practical manufacturing feasibility and the state-of-the-art. There is also no limit to the support plans that can be devised, except the very practical one of task entailed in getting the plan to work.

TABLE V-3
LEAST COST ESTIMATE

a. Systematic Elimination of Alternative Design & Support Configurations

System	Step	Compare Least Cost Estimates	Decision
B	1 ... 11	T_B, T_A	If: $\Delta T_{J,I} > 0$, choose alternative I; and if: $\Delta T_{J,I} < 0$, choose alternative J.
A	1 ... 11		
C	1 ... 11	T_C, min(T_B, T_A)	
...	...	...	
J	1 ... 11	T_J, min(T_I, ..., T_C, T_B, T_A)	
...	...	...	
N	1 ... 11	T_N, min(T_{N-1}, ..., T_J, ..., T_A)	

b. Hardware Alternatives for a Specific System (A)

Level	Alternative: Discard	Alternative: Repair
System	A	
Subsystem	A_{11}	A_{21}
Equipment	A_{21}	A_{22}
Assembly	A_{31}	A_{32}
Module	A_{41}	A_{42}
Part	A_{51}	

c. Hardware Cost Comparisons for Various Levels of Assemblies for System A

Step	Compare	Decision
1	T_{21}, T_{11}	If: $\Delta T_{j1,i1} > 0$, choose alternate A_{i1}; and if: $\Delta T_{j1,i1} < 0$, choose alternate A_{j1}.
2	T_{31}, min(T_{21}, T_{11})	
3	T_{41}, min(T_{31}, T_{21}, T_{11})	
4	T_{51}, min(T_{41}, T_{31}, T_{21}, T_{11})	

2

APPENDIX VI

LOGISTIC CRIETERIA AND METHODS FOR ESTABLISHING SPARES LEVELS

1. SUPPORT ENVIRONMENTS AND SPARING OPTIONS

The differences among design/support alternatives will lie in cost of spares, unused spares, or in cost in extra downtime. The method developed herein will involve determining the repair policy that will permit achievement of desired operational readiness at minimum cost.

There are four reasonable options for sparing a particular item, where organization, field, and depot are separate (barring contingency planning):

a. At

a. At organization, field, and depot.

b. At field and depot.

c. At depot.

d. Nowhere.

Figure VI-1 shows a typical supply organization.

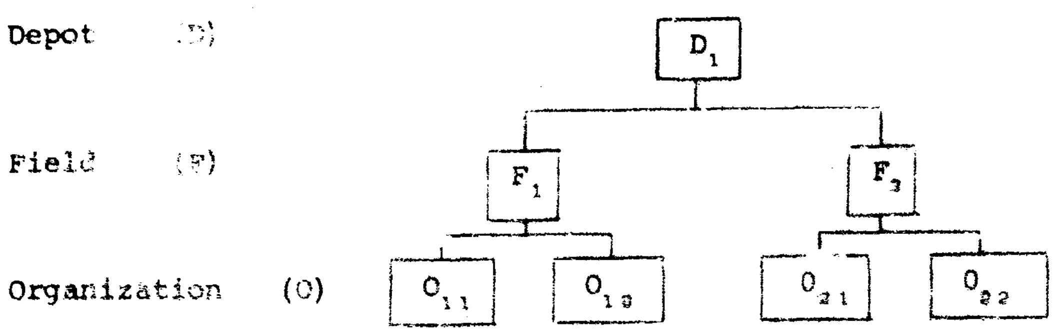


Figure VI-1 SUPPLY ORGANIZATION

A qualitiative comparison of costs and other characteristics can be made among options involving repair at organization, with repairs made at field or depot. This comparison is made in Table VI-1.

TABLE VI-1.

QUALITATIVE COMPARISON

Alternative	Frequency of Shortage	Usual Duration of Shortage	Obsolescence
Organization Spares	Low	Short	Greatest
Field Spares	All Failures	Short	Next Greatest
Depot Spares	All Failures	Longer	Less
No Spares	All Failures	Longest	None

Thus, the decision on sparing will often be concerned with where-to-spare, rather than whether-to-spare.

Table VI-2 presents the relative investment in inventory as a function of spares location.

TABLE VI-2.

INVENTORY

SPARES LOCATION	INVESTMENT
Organization	Greatest
Org., Field	Next Greatest
Org., Field, Depot	Least

Consider the case for organizational level sparing only; spares would have to be provided for every possible contingency, high failure rate or low failure rate, high usage item or low usage item. When multiplied by the number of organizations, the cost of maintaining this inventory would indeed be great. From the ranking (Table VI-2), it seems that the least inventory cost will occur when stocking spares at the depot, field, and organization. However, this least cost must be weighed against operational readiness requirements.

Table VI-3 presents relative cost of spares as a function of spares complexity (level of assembly).

TABLE VI-3.

SPARES SIZE

CATEGORY	RELATIVE COST
Parts	Least
Modules	Next Lowest
Higher Assemblies	Greater

The relations in Table VI-3 hold, because of the positive correlation between cost and size (part complexity).

The above observations suggest an iterative procedure for determining least cost spare location and category of spare. The procedure given below fits any case. Many of the cases, however, can be discarded by inspection, and only the feasible alternatives should be analyzed.

2. LOGISTIC CRITERIA

Several methods are used by the Government to determine the quantities of spares required for support of an equipment or system. There are many facets to sparing policy, e.g., strategic reserve, location of spares, running reserve, consumables, high-low value, and cost per item. Regardless of the methods used, some observations can be made about real differences in spares costs between design or support alternatives:

a. Spares are based upon anticipated usage, protection criteria, and cost.

b. Cost differences in sparing requirements will result from the different demands of design or support alternatives.

c. The difference in spares cost will be dependent upon the primary criterion invoked for sparing. There are three reasonable sparing criteria:

(1) Demand rate based on anticipated usage.

(2) Operational readiness (maximum return per unit investment).

(3) Confidence, maximum return in protection against outage per unit investment.

In general, there are two types of spares, consumables and repairables. The applicability of criterion (1) is limited to consumable parts, which permit bulk purchase, and cost-wise will be of a different order of magnitude from the higher level of assembly. Provisioning for repairables will be based on recycle times, which may involve tradeoff with repair location, test equipment (facilities, utilities), personnel, skill availability, and transportation costs.

The applicability of criteria (2) and (3) will depend upon particular circumstances; the significant difference between these criteria are illustrated in the following:

Attention is directed to the confidence method of protection and the unreadiness criterion.

The general characteristics of the different logistic system criteria are shown in figures VI-2 and VI-3. In each graph, a confidence and readiness curve is developed as a function of time (mission, turnaround, service). The parameters are spare (s) and expected demand (λt). Figure VI-2 has the parameters

$$s=2 \text{ and } \lambda t=1,$$

for which the confidence level is approximately 0.92, and the readiness is approximately 0.97. Figure VI-3 has the parameters

$$s=14 \text{ and } \lambda t=10,$$

for which the confidence level is approximately 0.92, and the readiness is approximately 0.99.

For ten components spared equally at a confidence level of approximately 0.92 (the exact values are used in the figures) the aggregate confidence level would be 0.433 for figure VI-2 and 0.418 for figure VI-3 Plotting these probability values on the respective illustrations for the confidence level method, it can be seen that the readiness level is much higher. The

readiness level for figure VI-2 is 0.81 and, more dramatically, the readiness level for figure VI-3 is 0.96.

Thus, for approximately the same confidence level for ten components (0.4), the actual readiness of the ten equipments is 0.81 for s=2, $\lambda t=1$ and 0.96 for s:14, $\lambda t=10$.

Two relevant questions are:

a. When will the logistic system run out of spares?

The answer is:

(1) For s=2, $\lambda t=1$, at a point 0.81 of the base time.

(2) For S=14, $\lambda t=10$, at a point 0.96 of mission completion.

b. How long will the logistic system be out of spares?

The answer is:

(1) For s=2, $\lambda t=1$, 0.19 of the time base.

(2) For s=14, $\lambda t=10$, 0.04 of the time base.

3. SPARES UNREADINESS MODELS

In general, unreadiness will be contibuted by spares at all levels of assembly. The aggregate amount of unreadiness contributed will depend on three basic considerations:

a. Number of spares, by type.

b. The demand for spares per unit calendar time, by type.

c. Service rate in filling a demand for a spare, by type.

The readiness numeric as developed in this report is the steady-state readiness or unreadiness.

Where different sources contribute unreadiness (e.g., two dependent repair echelons spare parts, spare repairable assemblies, and test equipment), the unreadiness contributions are additive if they are independent (e.g. paragraph 4 of this appendix). Care must be exercised to ensure that sources of unreadiness are not counted twice. It is to be noted that the different sources contibuting unreadiness may use different time bases for the purposes of computation and the results remain additive. Similarly, subsystem unreadiness contributions are additive where independence exists.

In section 4 of the test, a functional symbolism is developed, which is:

s_{i-jk}=s[support alternative, $u(\lambda,\mu)$],

where the subscripts designate respectively:

i=Specific type,
j=Level of assembly, and
k=Location.

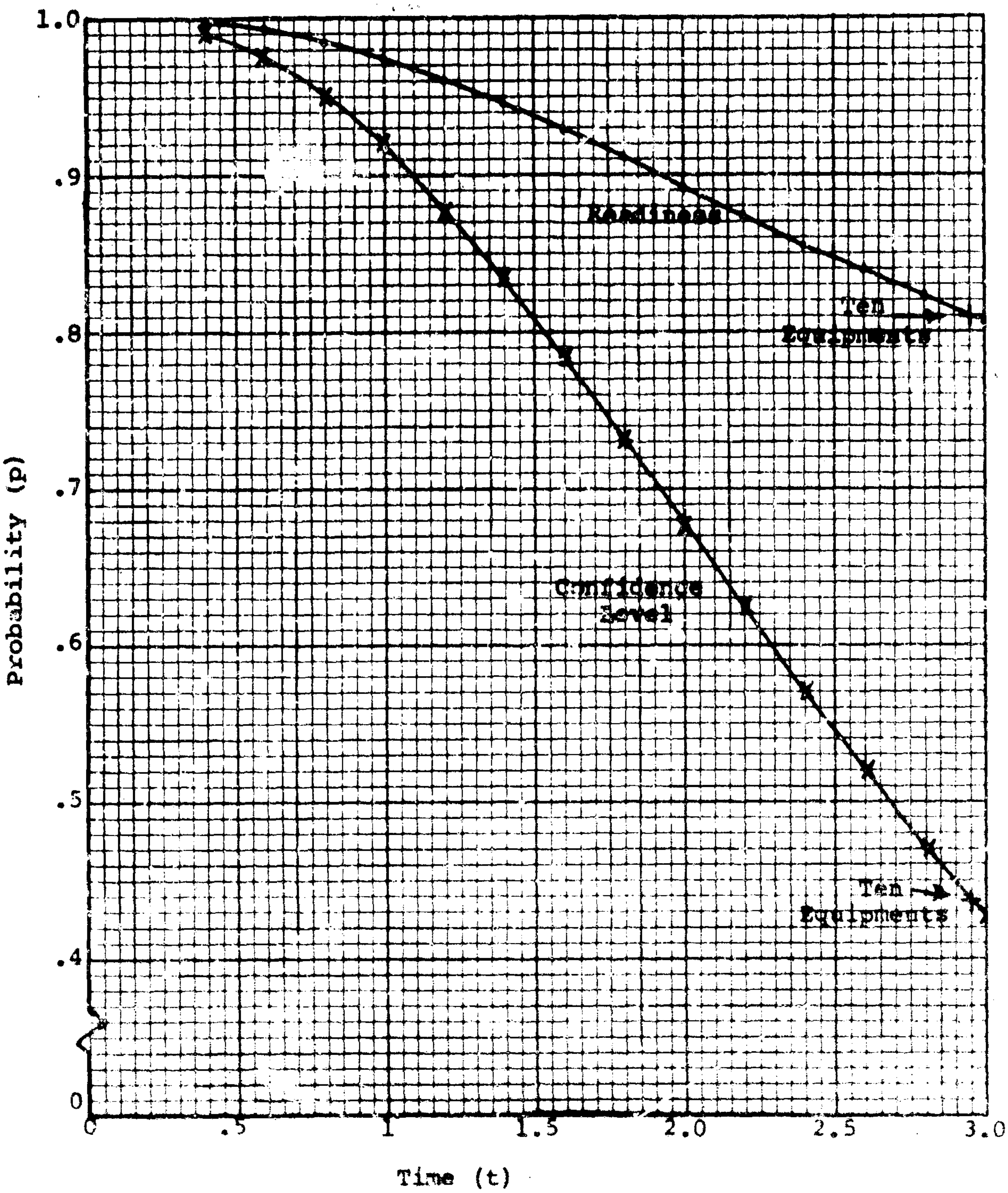


FIGURE VI-2. READINESS vs CONFIDENCE LEVEL METHODS

S=2, xt=1

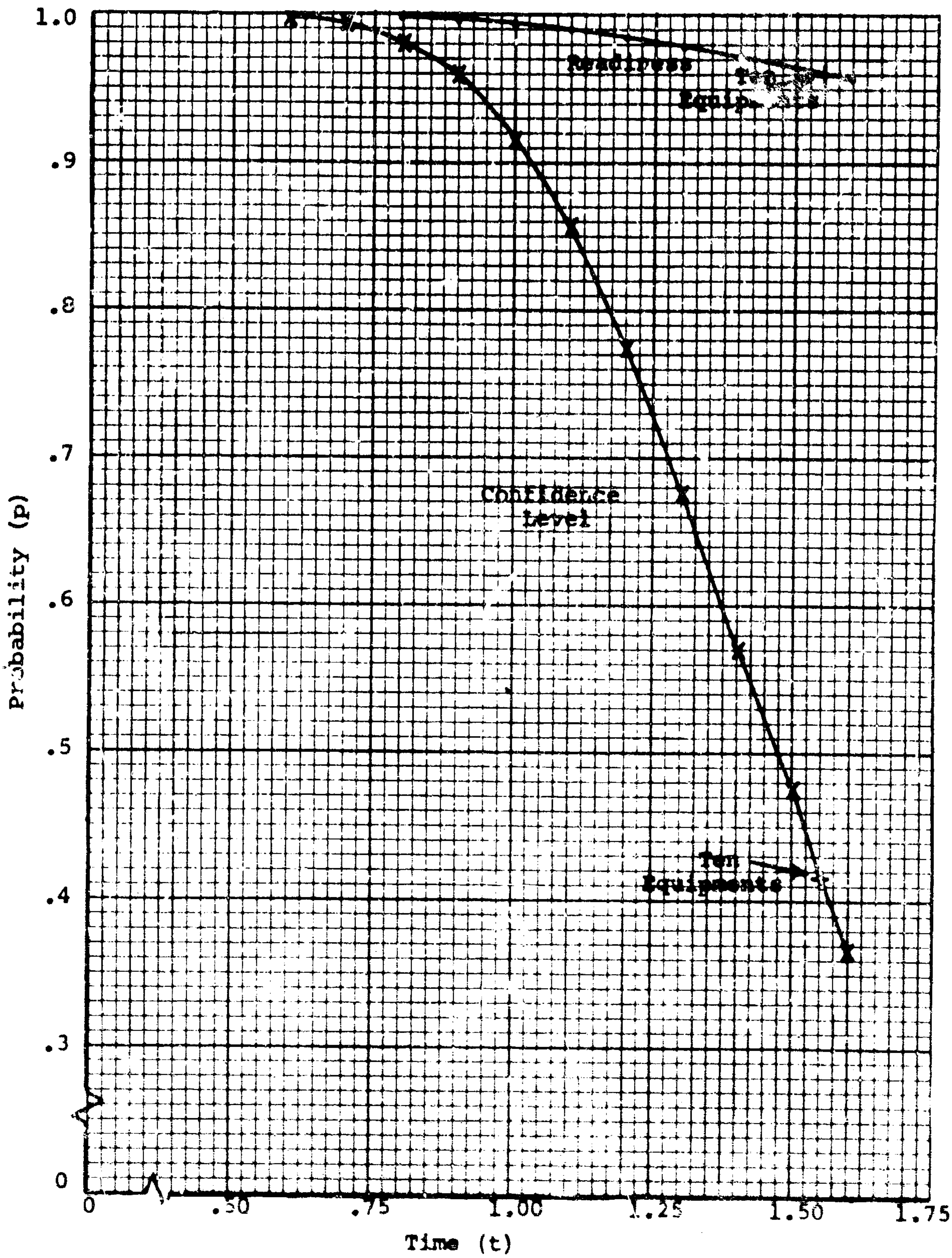


FIGURE VI-3 READINESS vs CONFIDENCE LEVEL METHOD

s=14, xt=10

The functional $u(\mu\lambda)$ implies that the unreadiness contribution is a function of:

μ=Service time, and

λ=Demand for service.

The total cost for all repairable spares is:

$$\text{Total Cost (Spares)} = \sum_{i}\sum_{j}\sum_{k} c_i s_{i-jk}$$

The subtlety in the foregoing is, of course, in determining s_{ijk}.

The purpose and rationale for the functional symbolism is that, usually, an optimization procedure will be involved to determine the actual required number of a specific type of spares. The type of optimization will depend upon the mechanics of the particular sparing problem (level of assembly and location).

Situations will arise in which careful attention is required of alternatives in terms of readiness return per unit expenditures; e.g., additional logistic support or additional operating units. A useful criterion for such tradeoffs is the concept of "Cost of Readiness."

If (N) end items are supported over a lifetime of (L) years at an operational readiness (1-u), the total ready time is:

T_r=NL(1-u)=Total expected readiness hours.

The imputed cost of readiness is:

$C_r=T/T_r=A+S/T_r$=Cost per unit readiness.

In the case of piece parts, unreadiness was not directly evaluated. The tacit assumption is that the quantities will be bulk-purchased, and that this will not be a major source of unreadiness. Where the foregoing assumption is not valid, this situation can be treated with the same leve of detail as higher level of assembly, using the models and examples developed subsequently.

4. COMPUTATION OF SPARES UNREADINESS

Spares unreadiness at a given level of assembly (higher than the discard level) at a given repair location is created according to the probability that shortage is developed for the higher level of assembly, coincidentally with a shortage at the lower level of assembly. Since the net effect of the unreadiness at

the lower level of assembly is to extend the service time, it is convenient and appropriate simply to adjust the mean service time of the higher level of assembly.

Similarly, a shortage due to spares at a higher echelon (field depot) for a given level of assembly is reflected in unreadiness at a lower echelon (organization, field), according to the probability that a shortage at the lower echelon occurs coincidentally with a shortage at the higher echelon. Again, since the result is to extend the service time of the next higher level of assembly at the lower echelon, it is appropriate to adjust the mean service time at the lower echelon.

Alternatively, it is appropriate simply to add the unreadiness contibutions from each level of assembly. Table VI-4 illustrates the methodology.

Actually, unreadiness always manifests itself through direct contact between the service channel and the end item being supported. Hence, a more accurate picture is protrayed by addition of waiting time for repairable spares or parts to the service time of the service channel having direct contact with the end item. Where unreadiness contributions are small, and u_i<0.1, simple addition of unreadiness contributions is recommended (Σu_i), where demand reates are based upon population (N_0), which compensates for unreadiness of the direct support service channel. Of course

$$N_0\lambda=N\lambda(1-u). \qquad \text{VI-a}$$

When computing unreadiness contributions of spares demands, it may be more convenient simply to modify the item failure rate by

$$\lambda^*=(1-u)\lambda. \qquad \text{VI-b}$$

A further complication arises when subsystems are significantly interdependent in unreadiness contribucions. Suppose there are (n) subsystems, each contributing (u_i) unreadiness.

$$u_i=f(s,C,\lambda,\mu,N) \qquad \text{VI-c}$$

If the subsystem (i) does not operate when another subystem (j) is in an unready state an appropriate modification is necessary to the demand rate of subsystem (i).

If u = unreadiness contributed at the direct support service channel

u_j= unreadiness contributed by sysbystem (j).

u_i = unreadiness contributed by subsystem (i)

λ_i = failure rate of subsystem (i)

A modified demand (failure) rate is established for subsystem (i) as a result of direct support unreadiness.

$$\lambda_i^{*}=(1-u)\lambda_i \qquad \text{VI-d}$$

This demand rate must be further modified as a result of unreadiness contributed by subsystem (j)

$$\lambda_i^{**}=(1-u-u_j)\lambda_i \qquad \text{VI-e}$$

or, if $u<0.1$
$u_j<0.1$

then $\lambda_i^{**}\cong(1-u_j)\lambda_i^{*}$ VI-f

This produces

$$u_i=f_i(s, C, \lambda^{**}, u, N) \qquad \text{VI-g}$$

Note that N, not N_0 is used in this case, from equation VI-a.

For each level of assembly for which spares are feasible at a given location, a range of unreadiness is established as a function of cost. This computation is based on minimization of unreadiness with respect to a cost allocation. The models to be used for this purpose will be found at the end of this appendix. This is done successively for each level of assembly.

For a particular combination of cost allocation to level of assembly, the aggregate cost and unreadiness is given by

$$u=u_{si}+u_{w}+u_{sx}$$

$$C=C_{si}+C_{wj}+C_{sx}.$$

Considering a given assembly level, the rate of return in unreadiness reduction may be computed for successive cost allocations.

This is shown symbolically in Table VI-5.

TABLE VI - 4

LEVEL OF ASSEMBLY		UNREADINESS/COST ALLOCATION ARRAY				
h	$u_{h0}/c_{h0}=0$	u_{h1}/c_{h1}	u_{h2}/c_{h2}	. . .	u_{hi}/c_{hi}	$u_{hi}>u_{hi}$ $c_{hi}<$
m	$u_{m0}/c_{m0}=0$	u_{m1}/c_{m1}	u_{m2}/c_{m2}	. . .	u_{mj}/c_{mj}	
p	$u_{p0}/c_{p0}=0$	u_{p1}/c_{p1}	u_{p2}/c_{p2}	. . .	u_{pk}/c_{pk}	

TABLE VI - 5

		UNREADINESS RETURN RATE			
h	r_{h1}	r_{h2}	. . .	r_{hi}	$r_{hj}=\frac{\Delta u_{hi}}{\Delta c_{hi}}=\frac{u_{hi}-u_{hj}}{c_{hj}-c_{hi}}$
	$\Delta u_{h1}/\Delta c_{h1}$	$\Delta u_{h2}/\Delta c_{h2}$	. . .	$\Delta u_{hi}/\Delta c_{hi}$	
m	r_{m1}	r_{m2}	. . .	r_{mi}	$r_{h1}=\frac{u_{h1}}{c_{h1}}$
	$\Delta u_{m1}/\Delta c_{m1}$	$\Delta u_{m2}/\Delta c_{m2}$	. . .	$\Delta u_{mj}/\Delta c_{mj}$	$r_{m1}=\frac{u_{m1}}{c_{m1}}$
p	r_{p1}	r_{p2}	. . .	r_{pk}	
	$\Delta u_{p1}/\Delta c_{p1}$	$u_{p2}/\Delta c_{p2}$	. . .	$\Delta u_{pk}/\Delta c_{pk}$	$r_{p1}=\frac{u_{p1}}{c_{p1}}$

2

5. OPTIMALITY CONDITION

The condition for optimality is given by

$$r_h = r_s = r_p, \text{ i.e.,}$$

the marginal returns for an additional cost investment is the same for all levels of assembly. The mechanics of achieving this condition follows:

Given: (1) unreadiness goal (u), (2) or total permissible cost, from the tabular array, determine if the unreadiness condition (u_0) can be satisfied with selection of one or a combination of entries from the first column of table VI-4, i.e., (c_{h1}) and/or (c_{s1}) and/or (c_{p1}). If yes, then the range must be extended to lower cost allocation. Select the entry (table VI-5) (c_{h1}), (c_{s1}), (c_{p1}) having the maximum (r_1). The allocation of one unit in this row and zero in the others is selected as the first feasible solution, and has associated with it in unreadiness (u') and (c'), where (u') is the sume of (u) in the selected row, or level of assembly, and the (u_0's) of the other rows. For example, if (r_{p1}) is chosen,

$$u' = u_{p1}, + u_{s0} + u_{h0}.$$

(c') is similarly determined.

If $u' < u$, an optimum allocation has been reached. If $u' > u$, select the maximum of (r_2) in the same row as the selected (r_1) and the unused (r_1's).

If $u' > u$, repeat the cycle. When the condition is reached such that

$$u'_n \leq u,$$

the associated optimum cost is

$$c = c_{hi} + c_{sj} + c_{pk},$$

where (i), (j), (k) correspond to the selected levels of spares for the three assembly levels.

The conversions and computations necessary for establishing unreadiness at the using location require the application of, at most, three logistic models; these models are special cases of one model which will be shown later.

6. MODEL 1

This model may be used for computation of:

a. Lifetime Discard Spares, with the parameters

t_i = L = Lifetime,

λ_i = failure rate, and

c_i = item cost.

b. Repair - Remote Repair (Field or Depot), with the parameters

t_i = service time (includes pipeline time, repair time),

λ_i = failure rate, and

c_i = item cost,

c. Discard - Reorder Time, with the parameters

t_i = re-order time,

λ_i = failure rate, and

c_i = item cost.

d. Repair - Local, with the parameters

t_i = service time at site,

λ_i = failure rate, and

c_i = item cost.

Limitations

The model is based on

a. Infinite population,

b. Exponential demand and service time, and

c. Single service channel.

6.1 GENERAL METHOD OF APPLICATION

Consider that spares are allocated to a specific location, viz., organization / field, or depot.

Let

t_i = service time required to restore an item to operational status (satisfy a demand),

i = item, and

P_{ij} = probability of more than (j) demands during period (t_i).

If (j) spares have been allocated to item type (i), the expected downtime, due to shortages of spares $(\bar{M}_{s-ij})$, will be as follows:

$$M_{s-ij}=t_i P_i/({}_{j+1}). \qquad \text{(VI-1)}$$

and the unreadiness (u_{ij}) will be

$$u_{ij}=\bar{M}_{s-ij}/t_i=P_{ij}/({}_{j+1}). \qquad \text{(VI-2)}$$

The incremental decrease in unreadiness (Δu_{ij}) due to adding another spare will be:

$$\Delta u_{ij}=[P_i({}_{j+1})/({}_{j+2})]-u_{ij}, \qquad \text{(VI-3)}$$

and the incremental decrease per unit cost(δ_{ij}) is

$$r_{ij}=\Delta u_{ij}/c_i,$$

where

c_i=cost of i.

The probability (P_{ij}) is computed by means of the Poisson distribution, using parameter (λ_i) (demand rate) and (t)(service time). Each item is assumed to contribute independently to unreadiness. Table VI-6 illustrates unreadiness as a function of demand rate (failure rate in this case) and service time (supply time in this case).

TABLE VI-6

UNREADINESS

Failure Rate λ (part/hours)	Spares											
	0	1	2	3	4	5	6	7	8	9	10	11
	Supply Cycle - 2 weeks											
.001	.285	.0226	.00164	.000102	.00000540	.00000025	.00000001	.00000000				
.0003	.0970	.00243	.0000546	.00000104	.00000002	.00000000	.00000000					
.0001	.0329	.000274	.00000204	.00000001	.00000000							
.00003	.0100	.0000248	.00000006	.00000000								
.00001	.00336	.00000280	.00000000									
.000003	.00101	.00000025	.00000000									
.000001	.000336	.00000003	.00000000									
.0000003	.000101	.00000000										
.0000001	.0000336	.00000000										
	Supply Cycle - 4 werks											
.001	.498	.0727	.0102	.00124	.000129	.0000118	.00000096	.00000007	.00000000			
.0003	.183	.00893	.000394	.0000148	.00000047	.00000001	.00000000	.00000000				
.0001	.0648	.00107	.0000159	.00000020	.00000000	.00000000						
.00003	.0198	.0000987	.00000044	.00000000								
.00001	.00668	.0000112	.00000002	.00000000								
.000003	.00200	.00000100	.00000000									
.000001	.000672	.00000011	.00000000									
.0000003	.000201	.00000001	.00000000									
.0000001	.0000672	.00000000										
	Supply Cycle - 6 weeks											
.001	.632	.132	.02677	.00475	.000732	.0000990	.0000119	.00000128	.00000013	.00000001	.00000000	
.0003	.261	.0187	.00122	.0000681	.00000326	.00000014	.00000000	.00000000	.00000000	.00000000		
.0001	.0970	.00243	.0000546	.00000104	.00000002	.00000000						
.00003	.0296	.000221	.00000147	.00000001	.00000000							
.00001	.0100	.0000248	.00000006	.00000000								
.000003	.00300	.00000225	.00000000									
.000001	.00101	.00000025	.00000000									
.0000003	.000302	.00000002	.00000000									
.0000001	.000101	.00000000										

2

It is required that unreadiness due to lack of spares be reduced so as to be compatible with an operational readiness goal. Let (u) be the permissible unreadiness. It will be more convenient to carry out the following steps, in some tabular form:

a. Of the (n) item types to be considered, compute (u_{ij}) and $(\sum_{i=1} u_{ij})$.

b. Compute (Δu_{ij}) for each of (n) item types, based on the addition of one spare.

c. Compute (r_{ij}) for each of (n) item types.

d. Chose maximum value of (r_{ij}) and compute the total unreadiness (u') as follows:

$$u' = \sum_{i=1}^{n} u_{ij} - \Delta u_{ij} \tag{VI-4}$$

where (Δu_{ij}) is paired with maximum value of (δ_{ij}).

e. Decision Rules:

(1) $u' \leq u$, STOP, the goal has been reached.

(2) $u' > u$, add another spares to this item type, recalculate (Δu_{ij}) and (r_{ij}).

f. Repeat steps 4 and 5, always adding spares, to maximum value of (r_{ij}), until the goal has been reached, viz., $(u_n > u)$.

The optimization procedure is shown in figure VI-4.

6.2 Spares Procurement - Example

Consider the problem of provisioning spare parts. The approach to sparing is based on the preceding method, using either (1) confidence, or (2) unreadiness criterion, which permits achievement of a fixed level of protection at minimum cost. The optimization procedures are similar, with one very important difference, that of the criterion.

Table VI-7 lists the results obtained in solving the problem of maximum protection at a fixed cost. The target cost is $650. A spares list is presented for fifty identical modules used on an equipment, with the protection level afforded and the cost incurred in sparing by the confidence and unreadiness methods.

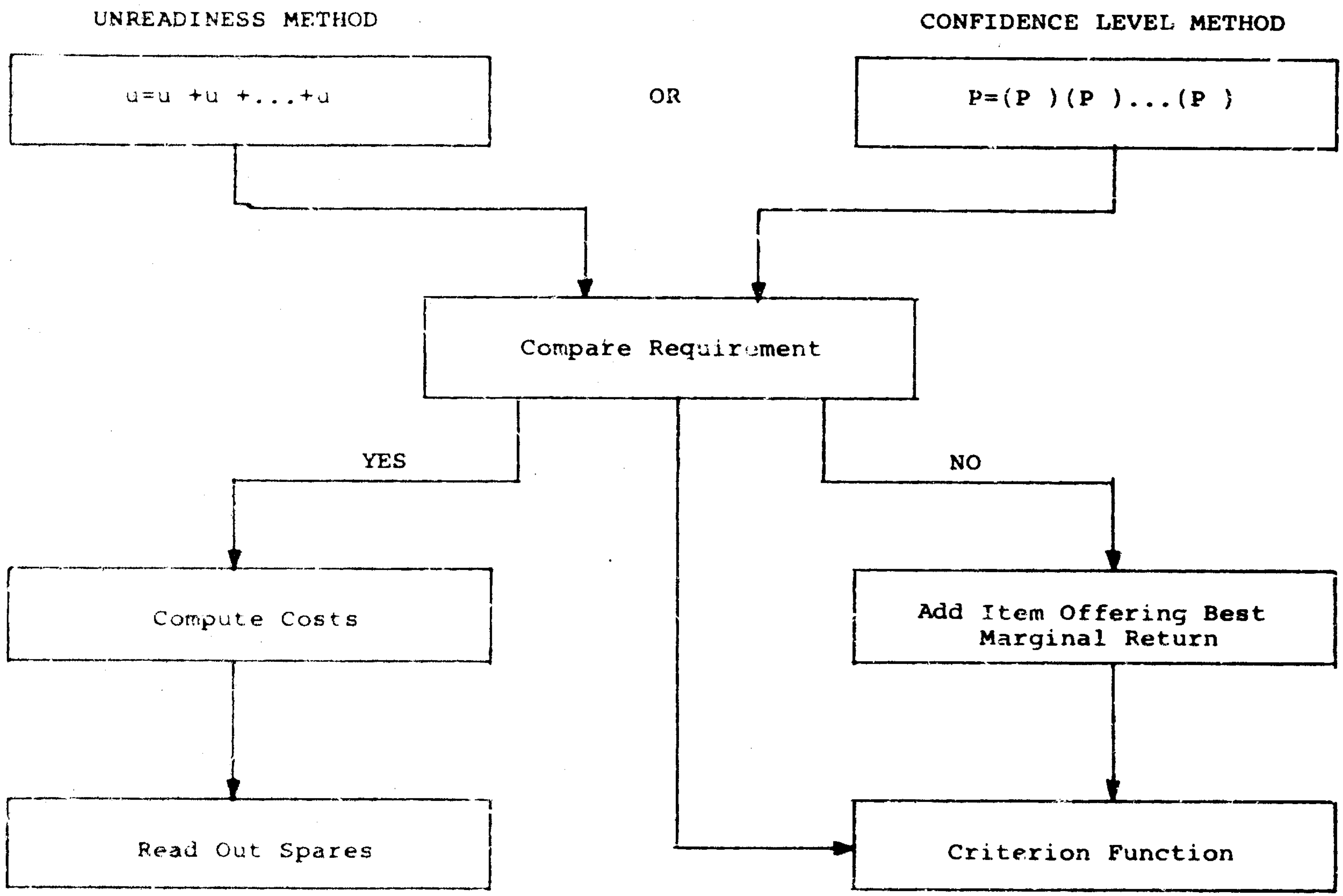


Figure VI-4 Protection At Minimum Cost

TABLE VI-7

COMPARATIVE SPARING LISTS

Part Class	Input: Replacement Rate λ	n	nλ	Cost c	nc	P	Sparing Method: Confidence	Unreadiness
	10^{-6}		10^{-6}	\$	\$	$n\lambda Nt_1$	j	j
Capacitor 1	3.0	50	150.0	0.80	40.00	7.500	24	25
Capacitor 2	0.8	3	2.4	0.60	1.80	0.120	4	5
Capacitor 3	0.5	3	1.5	0.50	1.50	0.075	4	5
Capacitor 4	0.1	1	0.1	1.50	1.50	0.005	2	2
Diode	3.0	2	6.0	3.30	6.60	0.300	5	6
Coil	0.1	11	1.1	3.90	42.90	0.055	3	3
Choke	2.0	22	44.0	5.00	110.00	2.200	11	12
Electron Tube	200.0	11	2200.0	3.00	33.00	110.000	161	157
Resistor 1	1.0	25	25.0	0.60	15.00	1.250	10	11
Resistor 2	0.4	35	14.0	0.10	3.50	0.700	7	9
Resistor 3	1.4	1	1.4	1.00	1.00	0.070	3	4
Transformer	0.5	12	6.0	9.50	114.00	0.300	5	5
Total		176	2451.5		370.80	122.575	239	244
				Cost			650.00	650.00
				Unreadiness (Ux10-8)			107	30
				Confidence Level (CL)			.99999003	.99998810
				q=[1-(CL)]x10-8			997	1190

λ= replacement rate per item
n= number of item per module
c= item cost

$P = \lambda n N t_1$
N= number of modules = 50
t_1 = provisioning time = 1000 hours

2

6.3 Parts vs. Modules

Let

λ = 0.123 part/hours, per equipment, and

μ = 0.5 per hour, repair time,

and assume there are no spare modules or equipments. The average unreadiness due to the failure and repair of the module, assuming a perfect supply system, will be

$$u_s = \lambda\mu = 0.246,$$

and the aggregate unreadiness, assuring the supply system developed in table VI-7, will be

$$u = u_s + u_p$$

$$= .24600024 \text{ (Unreadiness Method)}.$$

Following the method of Model 1, if an additional electron tube were added to decrease unreadiness, the marginal return would be

$$\Delta u_p = \frac{p_{i,j+1}}{j+2} - \frac{p_{i,j}}{j+1} = \frac{681}{158} - \frac{997}{157}\, 10^{-8} = (2)\ (10^{-8}), \text{ and}$$

$$r_p = \Delta u_p / c_i = (2)\ (10^{-8})/3.00 =)\ (0.67)(10^{-8}).$$

Let the cost of a repairable module be the sum of cost of the parts, viz., \$370.80. The return in readiness for adding one module is shown as

$$\Delta u_s = .205, \text{ and}$$

$$r_s = (55300)(10^{-8})$$

The unreadiness return ratio (r_s) formed by comparing the relative merits of acquiring a module versus adding a part is 82,500 to 1. A second spare module provides a return ratio 4900 to 1, a third 264 to 1, and a fourth, 12 to 1.

6.4 Life Time Discard Spares

The following example has been prepared to illustrate the different interpretations of service time and conditions under which spares will not be completely used. The total cost of discard items over the lifetime of the system is determined by the following model:

Let

j_i = number of spares, per item type, computed using provisioning model,

L = life of system, and

λ_i = total failure rate (calendar hour) per item type.

If

$$L\lambda_i \geq i,$$

the $(j_i c_i)$ is the total cost of the spare per item type.

If

$$L\lambda_i > j_i;$$
$$= j_i + t_i\lambda_i,$$

add $(L-t_i)\lambda_i$ spares to (j_i), the total cost $(j'_i c_i)$ then becomes

$$j_i c_i = [j_i + (L-t_i)\lambda_i]c_i. \qquad \text{(VI-5)}$$

Where spares are allocated only to the field or depot, downtime will occur for each demand at the organization.

The problem is as follows:

a. Determine spares of all types required at a site to meet operational readiness.

b. Determine total spares for all sites.

c. Determine additional spares by type, if any, for depot inventory. If spares by type, for all sites, exceed requirements for a single depot, based on total failures, the depot need not have spares of that type.

Table VI-8 was prepared to indicate spare requirements as a function of unreadiness, failure rate, and sparing location. Also shown, where applicable, are the unused spares at the end of life cycle as a result of meeting unreadiness conditions and minimum lifetime purchase requirements.

TABLE VI-8

SPARE REQUIREMENTS

λ	u	s_1	s_{10}	s_4	$L\lambda_1$	Δs_{10}	Δs_4	M	Δu	T_{10}	T_{14}
(10^x/yr.)	(10^x)				(10^x)				(10^x0)		
X=	X=				X=				X=		
-7		0	0	0	-5	0	0	0	-6	0	0
-6		0	0	0	-4	0	0	0	-5	0	0
-5		0	0	0	-3	0	0	0	-4	0	0
-4		0	0	0	-2	0	0	1	-3	1	1
-3	-3	0	0	2	-1	0	2	2	-2	2	2
-2		2	20	3	0	19	2	3	-1	20	3
-1		3	30	5	1	20	-5	5	0	30	10
0		5	50	18	2	-50	-82	18	1	100	100
1		18	180	125	3	-820	-875	125	2	1000	1000
-7		0	0	0	-5	0	0	0	-5	0	0
-6		0	0	0	-4	0	0	1	-4	1	1
-5		0	0	0	-3	0	0	1	-3	1	1
-4		0	0	1	-2	0	1	1	-2	1	1
-3	-4	1	10	2	-1	10	2	2	-1	10	2
-2		2	20	3	0	19	2	3	0	20	3
-1		3	30	7	1	20	-3	7	1	30	10
0		7	70	21	2	-30	-79	21	2	100	100
1		21	210	125	3	-790	-875	125	3	1000	1000
-7		0	0	0	-5	0	0	1	-4	1	1
-6		0	0	1	-4	0	1	1	-3	1	1
-5		1	10	2	-3	10	2	2	-2	10	2
-4		2	20	2	-2	20	2	2	-1	20	2
-3	-5	2	20	3	-1	20	3	3	0	20	3
-2		3	30	4	0	29	3	4	1	30	4
-1		4	40	8	1	30	-2	6	2	40	10
0		8	80	24	2	-20	-76	24	3	100	100
1		24	240	125	3	-760	-875	125	4	1000	1000
-7		1	10	2	-5	10	2	2	-3	10	2
-6		2	20	2	-4	20	2	2	-2	20	2
-5		2	20	2	-3	20	2	2	-1	20	2
-4		2	20	2	-2	20	2	2	0	20	2
-3	-6	2	20	3	-1	20	3	3	1	20	3
-2		3	30	4	0	29	3	4	2	30	4
-1		4	40	10	1	30	0	6	3	40	10
0		10	100	26	2	0	-74	26	4	100	100
1		26	260	140	3	-740	-860	140	5	1000	1000

2

where

λ_i = aggregate failure rate of item type per year,

u = unreadiness,

s_1 = initial spare requirements at one site,

s_{10} = initial spare requirements for 10 sites,

d_d = spare requirements if spares are located at depot,

$L\lambda_i$ = expected lifetime usage,

Δs_{10} = net difference between on-site spares required at 10 sites by unreadiness conditions, and expected lifetime demand (Plus equals unused, minus indicates reorder is necessary).

Δs_c = net difference between depot spares required by unreadiness conditions for 10 sites, and total lifetime demand.

$j't_s$ = total spares requirements for 10 sites, at site location, over lifetime of equipment.

$j't_d$ = total spares requirements for 10 sites, at depot location, over lifetime of equipment. Where depot spares for one year permit a one-each allocation to sites with some left over, it is anticipated that all spares would be kept at the depot. If spares were allocated to sites, a reduction in ureadiness due to the order time could be achieved.

M = minimum buy based on first year supply. If spare requirement is less than one, requirement is based on lifetime unreadiness permissible.

Δu = expected site unreadiness decrement resulting from depot delays, including transportation (if spare are centralized at depot).

Site unreadiness is determined by:

$N_{r-d}\,[t/YL]$ = site unreadiness,

where

N_{r-d} = number of depot demands,

t = transportation time per demand (.01 years),

Y = number of sites = 10, and

L = equipment life = 10 years.

7. MODEL 2

Model 2 is developed in appendix III.

This model is applicable at the replacement level of assembly, which contributes unreadiness directly to the end item being supported.

The method of application of the model is detailed in appendix III. This model is used to establish tradeoff conditions among major spare assemblies, personnel, scheduling, and unreadiness. Test equipment complements required to sustain service rates can be determined and traded with personnel and end item unreadiness.

8. MODEL 3

When the organizational or field repair consists of replacing a repairable spare, some unreadiness may be contributed by unavailability of repairable spares, while awaiting replenishment by the depot. The model used for this situation is a special case of Model 2, as described in appendix III, and uses the same tables. For Model 3, (c) designates number of spares, rather than service channels, as in Model 2. The service rate (u) is interpreted as the inverse of turnaround time for obtaining a spare from the depot. Other parameter definitions are unchanged, except for (s) (spares in Model 2) which is not used, since for Model 3, (s) always equals zero.

The behavior of Model 3 is illustrated in figure VI-5.

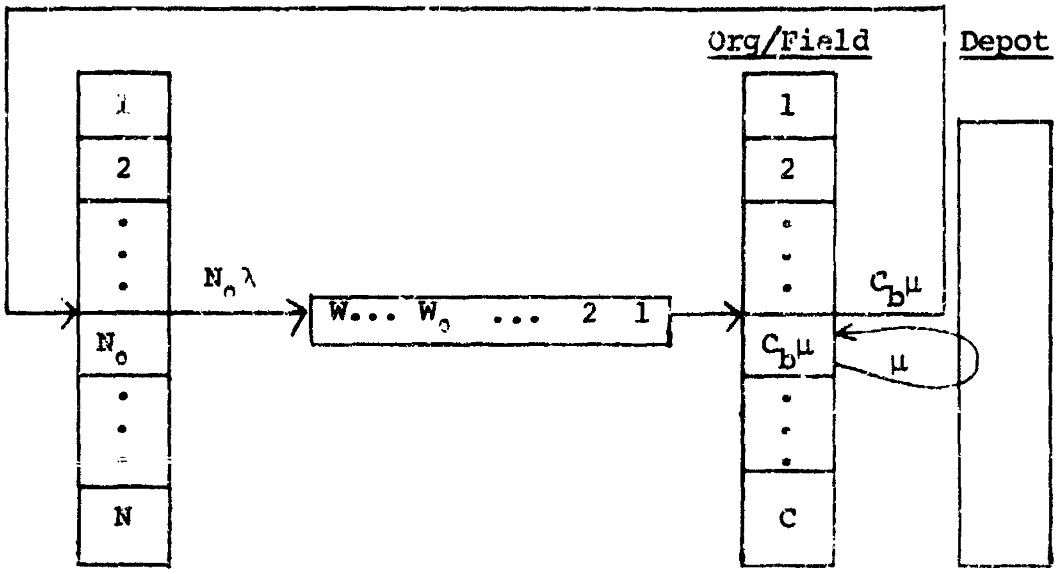


Figure VI-5.

To determine the unreadiness contribution from repairable spares at organization or field, it is only necessary to make appropriate parameter value replacements into the procedure for Model 2.

9. ERROR ANALYSIS OF UNREADINESS LEVELS

The interplay among the basic parameter inputs dictates the accuracy of the model performance. These parameters are:

t = Item time parameter,

B = Operational rate,

C = Item cost, and

λ = Failure rate.

The time parameter is important for consumable items (parts, non-repairable assemblies at location for periodic bulk order). In conjunction with the operational rate and failure rate, these parameters provide a best estimate of usage (subject to conditions below).

The expected usage is

$$p^* = \lambda Bt(1-u).$$

The error associated with p^* is measured by

$$\Delta p^* = (1-u)[\lambda B''t+t\Delta B\Delta\lambda].$$

(u) is the unreadiness, and is estimated using (p^*).

Suppose unreadiness levels (u_1^*) and (u_2^*) are established as minimum and maximum usable levels for a particular equipment. If item cost is introduced, the number of spares of each type to achieve (u_1^*) at minimum cost can be computed. This is repeated for (u_2^*), and difference in cost noted.

Error rates may be introduced to check the sensitivity of (u_1^*) and (u_2^*) with respect to cost, additionally, the range of (u_1^*) and (u_2^*) may be investigated by computing the minimum spares cost for (u_1^*), ($u_1^*+\Delta u$), ($+u_1^*+2\Delta u$), ($\ldots u_2^*-\Delta u$), ($u_2^*-2\Delta u\ldots$).

This sensitivity analysis provides a complete picture of cost variation as a function of (u^*) for an equipment, along with error implications in (u^*) as a function of ($\Delta\lambda$), (Δt), and (ΔB).

APPENDIX VII
PARTS SELECTION CRITERIA

1. COST ASPECTS

The purpose of this appendix is to present the development of cost aspects involved in selecting between alternative candidate parts to fulfill an objective. In this presentation of the subject, it is assumed that part type (a) is an established standard part in USAF Inventory. The decision making is based on simple incremental difference in total expected cost.

Let $$c_a - c_b = \Delta c,$$

where c_a = cost of part alternative (a), and

c_b = cost of part alternative (b).

The difference in costs between two candidate parts will arise from one of these sources.

a. Difference in failure rate.

b. Difference in unit cost.

c. Difference in fixed costs.

d. Difference in product improvement cost.

Let L = Expected life of system for which parts are being evaluated.

λ_a = failure rate of part type (a).

λ_b = failure rate of part type (b).

c_a = unit price of alternative (a).

c_b = unit price of alternative (b), a function of number purchased.

c_f = cost of failure measured by maintenance requirements (excluding part costs).

N = Number of application of part types (a) and (b).

P_b = Cost of product improvement program for parts (b).

N_a = Total number of part type (a) usage.

c_{ib} = Unit cost of ith part (b) used.

I = Cost of entering part type (b) into inventory.

The expected total cost difference becomes

$\Delta c = {}_a - c_b$

$= NL(\lambda_a - \lambda_b)c_f$ = difference in cost of maintenance.

$+N(1+L\lambda_a)c_a - \sum_{i=1}^{N(1+L\lambda_b)} c_{ib}$ = difference in cost due to usage.

$-P_b$ =cost of product improvement

$-I_b$ =cost of entrance of part type (b) in to AF Inventory.

$-Q_b$ =qualification cost for part (b) for compliance with military specifications.

The expression for Δc becomes

$$\Delta c = NL(\lambda_a - \lambda_b)c_f + (N+1)L\lambda_a c_a - \sum_{i=1}^{N(1+L\lambda_b)} c_{ib} - P_b - I_b - Q_b.$$

If $\Delta c > 0$, then type (b) is preferable.

2. BREAKEVEN COSTS

The breakeven cost(s) for part (b) are determined by setting $\Delta c = 0$: i.e.

a. $NL(\lambda_a - \lambda_b)c_f + N(1+L\lambda_a)c_a - N(1+L\lambda_b)c_b - (P_b + I_b + Q_b) = 0.$

b. for cost per failure

$$c_f \geq \frac{(P_b+I_b+Q_b+N(1+L\lambda_b)c_b-N(1+L\lambda_a)c_a}{NL(\lambda_a-\lambda_b)}.$$

c. for $\lambda_t \leq \frac{(P_b+Q_b+I_b)-N(1+L\lambda_a)c_a-NLc_f\lambda_a+Nc_b}{-(NLc_f+NLc_b)}.$

3. PRODUCT IMPROVEMENT TRADEOFF

A standard method in product improvement is to test out unreliable parts. The net effect of this is to enhance the operational reliability and reduce the production yield.

Let

$\Delta\lambda_{jb}$ = change in failure rate of party type (b) resulting from incrementing additional time to the j<u>th</u> time interval.

ΔP_{jb} = the incremental cost up to the j<u>th</u> interval in the product improvement program to acachieve $(\Delta\lambda_{jb})$, and

$\Delta\bar{U}_{jb}$ = average increase in unit price in part type (b) tested to the j<u>th</u> interval as a result of decreased yield.

The breakeven condition justifying further reduction in failure becomes

$$\lambda_b-\sum_{j=1}^{k}\Delta\lambda_{jb} \leq (P_b+\sum_{j=1}^{k}\Delta Pj_b+I_b+Q_b)-N(1+L\lambda_a)c_a+\frac{N(c_b+\sum_{j}^{k}\Delta c_{jb})-NLc_f\lambda_a}{NLc_b+\sum_{j}^{k}\Delta u_{jb})-NLc_f}$$

4. THE COST OF FAILURE

The cost of a failure involves basically two aspects:

a. The manpower and equipment required to restore the system to operability (see appenxid III). As pointed out elsewhere, the support system must be evaluated to determine if demonstrable changes are, in fact, brought about as a result of selection between alternatives, and

b. The cost of unreadiness. This aspect is at best fraught with many real as well as philosophic problems. First of all, there is the problem of translating the part failure rate into degraded states of system behavior (Methodology exists for this purpose). Secondly, there is the problem of cost of unreadiness. This problem may be approached as follows:

Let

c_t = total system cost estimate, and

R = readiness associated with system.

The,

$\frac{R}{c_t}$ = return in readiness per unit cost,

and let

ΔR = change in readiness resulting from a decrease in failure rate from choosing alternative b.

Then, if

$$\Delta c_r \leq \frac{\Delta R c_t}{R},$$

the imputation is that an increment of funds (Δc) is a justifiable expenditure to gain a return (ΔR) in readiness. The reduction in unreadiness (ΔR) referred to above is the result of the net reduction in failure rate. To translate this into terms of equation, a madification is required. This becomes

$$\Delta c = NL(\lambda_a - \lambda_b)c_f - \Delta c_r + N(1+L\lambda_a)c_a - N(1+L\lambda_b)c_b - (P_b + I_b + Q_b)$$

Note - For establishing the cost of part usage, a multiplier of (3) should be introduced to these terms (See appendix VIII).

APPENDIX VIII

COST CONSTANTS AND RELATED INFORMATION

1. GENERAL

Accurate prediction of the lifetime costs associated with a military system requires data from its future user, its designer, and its future manufacturer. The costs of design, development, and manufacture will be estimated, normally, almost entirely from data which the manufacturer has concerning his own operation, using procedures that he uses in estimating bids. The costs of operation and maintenance require data from two sources: (a) the manufacturer, providing estimates of failure and repair rates, skills and test equipment required, cost of spares, etc. and (b) the Government, providing costs of human resources, handling, and the like.

This appendix lists values which have been used in application of the techniques described in this report. Much work remains to be done to develop more refined estimates of many of these cost element values. The listed values are the best available to the authors, and can result in useful problem solutions.

2. PERSONNEL COSTS

2.1 General

Personnel cost is based on the following:

a. Skill level.

b. Longevity.

c. Rations.

d. Quarters allowance.

e. Clothing allowance.

f. Retirement.

g. Training cost.

2.2 Pay

Cost contributions (a) through (e) are combined in the Standard Basic Rate Table (AFM 177-101) 1964. These standard rates are listed in table III-1, by skill level.

2.3 Retirement Cost

The contribution to personnel cost from retirement is obtained as follows:

P_i = probability of remaining in service until retirement given that the man has reached skill level (i).

r_i = rate of pay at retirement.

t_{si} = expected retirement time in years.

S_{ri} = expected retirement cost per year.

The cost of retirement for a man of skill level (i) (S_{ri}), per year, becomes as follows:

$$S_{ri} = p_i t_{si} r_i / 40$$

Time to retirement is assumed to be 20 years and the time in retirement 30 years (two assumptions are involved here: (1) time before and (2) after retirement; the assumptions tend to cancel out the errors involved).

Values for p_i :

E-3 or below	$p_3=0.00$
E-5	$p_5=0.10$
E-7	$p_7=0.75$
E-9	$p_9=1.00$

These values were established from data at Seymour Johnson AFB.

The base pay at retirement:

E-1	$r_1=1,344$

E-3	r_3=2,030
E-5	r_5=3,444
E-7	r_7=4,536
E-9	r_9=5,940

Values for S_{ri} based on pay at retirement:

E-3 or below	S_{r3}= 0
E-5	S_{r5}= 252
E-7	S_{r7}=2,531
E-9	S_{r9}=4,383

2.4 Training Cost

The training costs vary significantly between skill fields, which are dependent on hardware design. The training costs incurred, which include basic and specialized, are charged based on the number of replacement personnel required by the system under consideration. Training of personnel already trained represents funds already spent and these should not be charged against a potential system. Training costs should be based on Standard Military Basic Pay and Allowances Rate by skill level.

2.5 Summary

Total personnel cost, by skill level, is shown in table VIII-1. The values shown under year total do not include the cost of training. Training is shown in a separate column as a per month training charge, since the amount of training time varies widely for skill fields.

TABLE VIII-1

TOTAL COST BY SKILL LEVEL

Skill Level	Standard Basic Rate	Base Pay at Retirement	Retirement Cost	Year Total	Training (Per Month)
E-1	2,292	1,344	0	2,292	191
E-3	2,724	2,030	0	2,724	-
E-5	4,920	3,444	252	5,172	-
E-7	6,408	4,536	2,531	8,939	-
E-9	8,040	5,940	4,383	12,423	-

3. DEPOT LABOR COST

This cost is obtained from the appropriate Command Workload Group, e.g., Fire Control Systems, Directorate of Material Management, at the Air Force Depot of concern. This labor cost consists of direct and indirect cost, with the indirect cost comprising supervision, overhead, and benefits. For WRMMA these costs are:

Direct Labor $2.54 per hour
Indirect $3.36 per hour

For SAMMA the given total cost per labor hour is $8.08.

4. PERSONNEL BACKUP FACTOR

Additional personnel must be provided to fill vacancies resulting from sick leave, furlough, etc. The backup factor used is 0.2, meaning that manning is increased more than 20 percent by adding the backup per subsystem skill level, rounding upward.

The value for backup factor was obtained from AFM 26-1.

5. PARTS USAGE FACTOR

The parts usage factor was obtained from an analysis of field failure data, viz., three parts replaced per one failure (reference RADC TN-58-307 15 August 1958).

6. TRANSPORTATION COST

Transportation cost by commercial air freight varies significantly with distance and weight. There are usually minimum charges, e.g., $4.70 from 1 to 54 pounds. If commercial air freight is used for item shipment, precise quotes may be obtained from Air Freight Agencies. Where regular MATS is used, which will generally be the case, no charge should be incurred, since the absence of shipment would not influence the service. Where special MATS flights are involved, the cost incurred should be based on fuel consuption only.

Where commercial rail or trucking is used, shipment may be obtained. Where service vehicles are used, fuel consumption, and sustenance per trip should be charged. Personnel vehicles are charged only if the location required additional personnel and/or vehicles to perform this service.

7. SUPPLY COSTS

The following supply cost factors are used:

I = Cost of line item entrance into the supply system = $34.00

M = Cost of maintaining a line item in the supply system, Per year = $19.00

D = Repair documentation (Debit and Credit) = $14.00

R = Cost of maintaining a stock item in the Master Repair Schedule (MRS), per year = $29.00

Line item entrance cost (I) was obtained from AFLCR 400-20, and AFSCR 400-4, dated 14 February 1964.

Line item maintenance cost (M), repair documentation cost (D), and the cost of maintaining a stock item in the MRS (R), were obtained from RADC-TDR-63-140, AD405779, March 1963.

APPENDIX IX

VALUE ENGINEERING TECHNIQUE APPLICATION

1. INTRODUCTION

The value engineering technique described in this report provides the opportunity for value engineering throughout the range of system concept and development. It also lends itself to application at any required level of analysis detail. It remains the responsibility of the Value Engineer, however, to choose the appropriate level of detail required for practical decision-making at the existing level of system development. To provide some insight regarding the practical application of the technique, this appendix will examine a hypothetical system in which the value engineering technique is applied in the proposal phase. Although the example is hypothetical, it is similar to an application actually accomplished.

2. THE SYSTEM

A ground electronics system is being proposed for aircraft mission and traffic control. The system is comprised of Radar, Data Processing, and Communications subsystems.

Three squadrons are planned, each including three radar sites and a Command and Control Center. Each radar site has a radar, associated data processing, and communications.

Maintenance support is provided by a squadron maintenance van assigned to each squadron, and a field shop assigned to the wing.

The following maintenance policies will be applied:

a. Failure at a radar site will be localized to the degree possible by operator personnel, with assistance of the data processing equipment where feasible.

b. If a spare is carried on-site, the operator personnel will correct the failure and request a replacement spare by radio. The replacement will be delivered from the squadron maintenance van, by small vehicle. When the replacement is delivered, the failed item will be picked up for detail repair.

c. If a spare is not carried on-site, the operator personnel will call squadron maintenance, and transmit localization data to the degree available. Squadron maintenance personnel will proceed to site with anticipated test equipment and spares requirements.

2.1 Alternatives

Alternatives to be investigated include:

a. Subassembly discard or repair.

b. Automatic fault isolation or manual isolation using special or general purpose equipment.

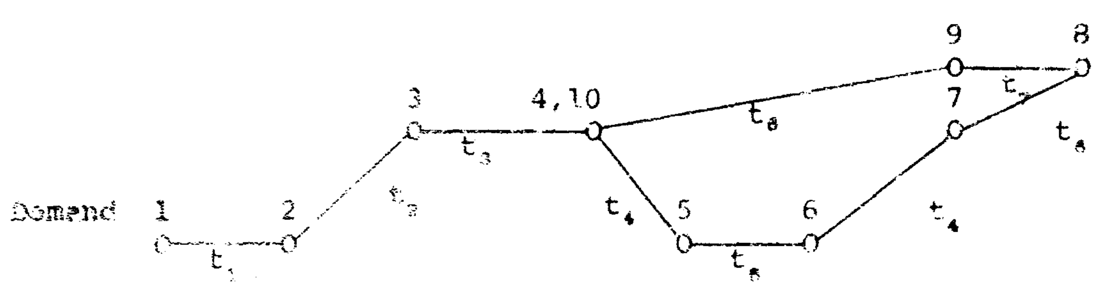
c. Assembly repair at squadron or field shop.

d. Assembly spares at site or squadron maintenance van.

2.2 The Support Structure

In order to reduce analytical requirements, the most economic support alternative will be analyzed first, with subassembly repair. If the alternative is feasible, it will be compared with the discard alternative.

The network below illustrates the activities of the first support alternative.



a. Failure occurs.

b. Failure is isolated to level I_0 by operator.

c. Localization data transmitted to squadron.

d. Spare is obtained from ready inventory at squadron.

e. Squadron personnel travel to site.

f. Failure is further isolated to replaceable subassembly, failed item is removed and replaced, subsystem checked out.

g. Failed unit is returned to squadron for field shop pickup.

h. Failed unit is returned to field shop for repair.

i. Repair is accomplished.

j. Repaired unit is returned to ready inventory at squadron.

t_i is the action time required to accomplish the following event.

In this alternative, no spares are carried on-site, except those built-in as redundant units. A single spare is kept at squadron maintenance for each assembly type. All repair of assemblies is accomplished in the field shop. Repaired units are delivered to the squadron maintenance van daily, using vehicles assigned to the wing. Pickup at squadron for field shop repair is accomplished on the same trip. Since volume is small, deliveries are combined with those for supply, mail, etc.

2.2.2 Support Structure Analysis

Analysis is required to determine whether this alternative is capable of meeting the operational readiness requirement

R=0.9

The following procedure will be followed:

a. Analyze field shop workload, determine mean downtime contribution (t_{wd}=waiting time for units in excess of spares).

b. Analyze squadron workload.

c. Combine field shop and squadron contributions with site-contributed unreadiness, to determine system unreadiness.

Table IX-1 describes the radar skill/hardware package, as allocated for repair by radar skills.

Table IX-1 Radar Skill/Hardware Package

	RADAR SITE						CCC
	H. V. POWER	AMP EXCITER	R. F. AMP	SIGNAL PROCESS	DATA COMM.	DISPLAYS	DISPLAYS
λ	10^{-5}	$7x10^{-4}$	10^{-3}	$2.7x10^{-3}$	10^{-4}	$1.3x10^{-3}$	$1.3x10^{-3}$
t_i	0.2	0.5	0.5	1.0	1.0	1.0	1.0
	0.1	0.2	0.2	0.5	0.5	0.5	0.5
	0.02	0.1	0.1	0.1	0.1	0.1	0.1
t	0.5	1.0	0.5	4.0	4.0	4.0	4.0
n	1	2	8	1	1	2	3
$n\lambda$	10^{-5}	$1.4x10^{-3}$	$8x10^{-3}$	$2.7x10^{-3}$	10^{-4}	$2.6x10^{-3}$	$3.9x10^{-3}$
s	0	1	1	0	0	1	2
λ_t						0.0148	0.0039

λ = item demand rate per operational hour.

t_i = isolation time to level I_0 by manual means, general/special test equipment/automatic means.

t = on-site repair time, including isolation from level I_0, removal, replacement, checkout.

n = number of applications of item in equipment.

s = number of spares built-in as redundant units (active).

λ_t = total demand rate of the equipment.

As described in Appendix III-9.5 for field shop and squadron workloads, the aggregate failure rate is used for actively redundant assemblies, and the redundant units are considered as spares.

Analysis is simplified by dividing the contribution of the Command and Control Center by three and grouping with the contribution of the radar site.

The demand rate of the radar skill/hardware package is then

$$\lambda_{pr}=0.0148+0.0039/3=0.0161$$

The remaining skill/hardware packages are described in Tables IX-2 and IX-3.

Table IX-2. Data Processing Skill/Hardware Package

	Radar Site			Command And Control Center	
	DATA PROCESS.	POWER SUPPLY	INPUT/ OUTPUT	CONTROL PROCESS.	MEMORY MODULE
λ	2.6×10^{-4}	10^{-8}	2.5×10^{-4}	5×10^{-4}	10^{-4}
t_i	1.0	1.0	1.0	1.0	1.0
	0.5	0.5	0.5	0.5	0.5
	0.1	0.1	0.1	0.1	0.1
t	4.0	4.0	4.0	4.0	4.0
n	1	1	1	2	8
$n\lambda$	2.6×10^{-4}	10^{-8}	2.5×10^{-4}	10^{-3}	8×10^{-4}
s	0	0	0	1	4
λ_t	0.00026				0.00205

The demand rate of the data processing skill/hardware package is:

$$\lambda_{pd}=0.00026+0.00205/3=0.00094$$

Table IX-3. Communications Skill/
Hardware Package

	Radar Site			Command and Control Center		
	XMTR	RECEIVER	DATA	XMTR	RECEIVER	DATA
λ	3×10^{-4}	3.5×10^{-4}	8×10^{-4}	3×10^{-4}	3.5×10^{-4}	8×10^{-4}
t_i	1.0	1.0	1.0	1.0	1.0	1.0
	0.5	0.5	0.5	0.5	0.5	0.5
	0.1	0.1	0.1	0.1	0.1	0.1
t	4.0	3.0	3	4.0	3.0	3.0
n	1	1	1	1	1	1
$n\lambda$	3×10^{-4}	3.5×10^{-4}	8×10^{4}	3×10^{-4}	3.5×10^{-4}	8×10^{-4}
s	0	0	0	0	0	0
λ_t			0.00145			0.00145

The demand rate of the communications skill/hardware package is:

$$\lambda_{pc}=0.00145+0.00145/3=0.00193$$

The field shop unreadiness contribution is determined for two feasible values. The values selected are

$$t_f=1/\mu_f=4,8.$$

The four-hour repair time is considered feasible with equipment mockups for isolation and checkout, whereas the eight-hour value is reasonable for use of general purpose equipment.

Table IX-4 is constructed to depict the spectrum of field shop maintenance contributions.

It is of interest to note the considerable magnitudes of the unreadiness numeric (d) and of waiting time(t_{wait}), for eight-hour repair time with a single repair channel. The reason is that the workload generated (NP) is greater than one, meaning

Table IX-4

Field Shop Repair Delay

$N_f=9$

Radar $t_f=8$ $\lambda=0.016$ $P=0.13$

	C=1		C=2	
	s=3	s=6	s=3	s=6
d_f	0.208	0.179	0.023	0.005
t_{wdf}	16.2	13.2	1.5	0.3

$t_f=4$ $P=0.06$

	C=1		C=2	
	s=3	s=6	s=3	s=6
	0.013	0.002	0.001	<0.001
	0.8	0.12	0.06	------

Data Processing $t_f=8$ $\lambda=0.001$ $P<0.02$

	C=1
	s=3
d_f	<0.001
t_{wdf}	<0.5

Communications $t_f=8$ $\lambda=0.002$ $P<0.02$

	C=1
	s=3
d_f	<0.001
t_{wdf}	<0.5

that a single repair channel cannot possibly maintain a stable queue unless demands are reduced by a significant number of inoperative units. With random demand and/or service rates, this situation arrives at $(NP<1)$. It is obvious, therefore, that if field shop repair time is eight hours, two repair channels must be assigned. A note is made at this point, to investigate the relative costs of a repair channel vs. the equipment mockup. Analysis is continued using the eight-hour repair time with two channels, as the worse of the two options, in the interest of decisions on the initially given alternatives, with minimum delay.

In addition to waiting for assembly repair, the field shop makes an unreadiness contribution through the travel delay from the field shop to the squadron. Since this travel time has importance only when the squadron is out of spares, the problem is handled as a four-channel queue, since $(N+S=4)$ assemblies could be delivered on one trip. One spare is normally carried at squadron.

Since the personnel and facilities are common to all items supported, the delay is common to all, and

$$N=3$$

$$P=\lambda_t T_f \qquad \text{IX-1}$$

Where λ_t = the aggregate demand rate from all three skill/hardware packages.

T_f = travel delay from the field shop.

The travel time is estimated at four hours. For daily scheduled delivery, an additional delay is introduced with a mean of twelve hours.

$$\therefore T_f = 4+12=16 \text{ hours}$$

$$\lambda_t = 0.0161+0.0020+0.0014$$

$$P = \lambda_t T_f=0.3$$

Table IX-5 shows the effect of travel delay, for one or two spares.

Table IX-5. Field Shop Travel Delay

$N=3$, $P=0.3$

$C=4$

	s=1	s=2
d_t	0.082	0.022
t_{wdt}	4.5	1.2

The workload of squadron maintenance includes the following elements:

a. Travel to radar site=T_s.

b. Removal, replacement, checkout = t.

c. Return to squadron with failed item = T_s

Unreadiness is contributed at this level by squadron personnel unreadiness, spares unreadiness, and travel.

Personnel unreadiness is analyzed by use of queuing tables, using

$N_t=3$

$p=\lambda t_s$

Where t_s is total time required for a squadron maintenance man to service a failure.

$t_s=2T_s+t$

For the radar,

$$t=\Sigma\lambda_{ir}t/\lambda_{pr} \qquad \text{IX-2}$$

$$=(0.5x10^{-5}+1.4x10^{-3}.4x10^{-3}.10.8x10^{-3}+4x10^{-4}$$
$$+10.4x10^{-3}+5.2x10^{-3})/0.0161$$

$$=2.0 \text{ hours}$$

Similarly, for Data Processing

$$t= 4.0 \text{ hours.}$$

and for Communications

$$t=3.2 \text{ hours.}$$

At this point in the proposal, all sites have not been assigned but possible locations range to mean distances of 40 to 80 miles from squadron maintenance locations. In the interest of early decision making, the worst case is first assumed, to assess its effect. Travel time is estimated at four hours.

For the radar

$$T_s=4$$

$$t_s=2x4+2.0=10.0$$

$$P=10.0x0.0161=0.16$$

Squadron repair delay is analyzed using Table IX-6.

The total unreadiness of the hardware/skill package is determined differently for redundant and non-redundant equipments. For non-redundant equipments, unreadiness is

$$d=\lambda_s t_d \qquad \text{IX-3}$$

Where (λ_s) is the failure rate of non-redundant equipment and (t_d) is expected downtime per failure.

$$t_d=t_{rdf}+t_{sdt}+t_{wds}+t_j+T_s+t \qquad \text{IX-4}$$

For simply active redundant equipments, unreadiness is

$$u=d^n \qquad \text{IX-5}$$

TABLE IX-6

Squadron Repair Delay

$N=3$, $t_s=10$, $P=10\lambda$

Radar $\lambda=0.016$, $P=0.16$

	C=1		C=2	
	s=1	s=2	s=1	s=2
d_s	0.077	0.036	0.032	0.008
t_{wds}	[illegible]	2.2	2.0	0.5

Communications $\lambda=0.001$, $P=0.01$

	C=1		C=2	
	s=1	s=2	s=1	s=2
d_s	0.001	---	---	---
t_{wds}	0.5	---	---	---

Data Processing $\lambda=0.002$, $P=0.02$

	C=1		C=2	
	s=1	s=2	s=1	s=2
d_s	0.002	---	<0.001	---
t_{wds}	1.0	---	<0.5	---

where

n=the number of failures necessary to disable the function.

$d=\lambda_r t_d$

and

λ_r=failure rate of equipment for which redundancy is provided.

For partial redundancy, where (m) must operate of (n) units provided for satisfactory performance, unreadiness is determined by the number of failures required for disability, multiplied by the possible number of combinations.

If

$n=8, \quad m=7$

Two failures are disabling, and unreadiness is

$$\frac{n!\,d^2}{p!\,(n-p)!} = \frac{8!\,d_2}{2!\,(6!)} = 28 [illegible] \qquad \text{IX-6}$$

In Tables IX-7, IX-8, and IX-9, unreadiness is computed for the three hardware/skill packages, for one and two spares at squadron. Using one spare, site operational readiness is computed as

$R \cong 1-\Sigma u_i = 90.6\%$

and, more precisely,

$R=\Pi(1-u_i)=90.9\%$.

This satisfies the requirement for operational readiness.

If the operational readiness requirement were not met, the tables indicate the most effective avenues for improvement. The following procedure would be used.

From Tables IX-7, IX-8, and IX-9, it can be seen that the greatest logistic contributors to unreadiness are field shop travel delay (t_{rdt}) and squadron unreadiness (t_{vsd}). Travel

TABLE IX 7

RADAR UNREADINESS

	1	2	3	4	5	6	7	8	9	10	11
	t_1	t	t_{w4r}	t_{w4t}	t_{w1s}	T_s	$t_d=\sum_1^6 t$	$\lambda x10^4$	$d=\lambda t_d$	$f(d)$	$u x10^4$
Site											
H. V. Pow.	0.2	0.5	1.5	4.5	5.2	4.0	15.9	0.1	1.6	d	1.6
s=2	"	"	0.5	1.2	2.2	"	8.6	"	0.9	"	0.9
Amp Exc.	0.5	1.0	1.5	4.5	5.2	4.0	16.7	7	117	d^2	1.4
s=2	"	"	0.5	1.2	2.2	"	9.4	"	65.8	"	0.4
R. F. Amp.	0.5	0.5	1.5	4.5	5.2	4.0	16.2	10	162	$28d^2$	73.5
s=2	"	"	0.5	1.2	2.2	"	8.9	"	89.0	"	22.2
Sig. Proc.	1.0	4.0	1.5	4.5	5.2	4.0	19.2	27	518	d	518
s=2	"	"	0.5	1.2	2.2	4.0	12.9	"	348	"	348
Data Comm.	1.0	4.0	1.5	4.5	5.2	4.0	19.2	1	19.2	d	19.2
s=2	"	"	0.5	1.2	2.2	"	12.9	"	12.9	"	12.9
Displ.	1.0	4.0	1.5	4.5	5.2	4.0	19.2	1.3	250	d^2	6.2
s=2	"	"	0.5	1.2	2.2	"	12.9	"	166	"	2.8
CCC Displ.	1.0	4.0	1.5	4.5	5.2	4.0	19.2	$\frac{13}{3}$	83.2	d^3	0
s=2	"	"	0.3	1.2	2.2	4.0	12.9	"	55.9	"	0

TOTAL Σu=0.0620, 0.0390

$\Pi(1-u)$=0.93856

2

TABLE IX-8

DATA PROCESSING UNREADINESS

	1	2	3	4	5	6	7	8	9	10	11
	t_i	τ	t_{wtr}	t_{det}	t_{rdm}	T_s	t_d	$\lambda x10^4$	$d=\lambda t_d$ $x10^4$	f(d)	$ux10^4$
Site DPE	1.0	4.0	0.5	4.5	0.5	4.0	15.0	2.6	39.0	d	39.0
s=2	"	"	0	1.2	0	"	10.2	"	26.5	"	26.5
CC[illegible]	1.0	4.0	0.5	4.5	0.5	4.0	15.0	1/3	0.5	d	0.5
s=2	"	"	0	1.2	0.	"	10.2	"	0.3	"	0.3
I/O	1.0	4.0	0.5	4.5	0.5	4.0	15.0	$\frac{2.5}{3}$	12.5	d	12.5
s=2	"	"	0	1.2	0	"	10.2	"	8.5	"	8.5
Cont Proc.	1.0	4.0	0.5	4.5	0.5	4.0	15.0	5/3	25.0	d^2	0
s=2	"	"	0	1.2	0	"	10.2	"	17.0	"	0
Memory	1.0	4.0	0.5	4.5	0.5	4.0	15.0	1/3	5.0	$4d^2$	0.01
s=2	"	"	0	1.2	0	2.0	10.2	"	3.4	"	0

Σu=0.0052, 0.0035

$\Pi(1-u)$=0.99480

2

TABLE IX-9

COMMUNICATIONS UNREADINESS

	1	2	3	4	5	6	7	8	9	10	11
	t_1	t	t_{war}	t_{wat}	t_{was}	T_s	t_d	$\lambda x10^4$	$d=\lambda t_d$ $x10^4$	f(d)	$ux10^4$
Site											
Xmtr	1.0	4.0	0.5	4.5	1.0	4.0	14.5	3.0	43.5	d	43.5
m=2	1.0	4.0	0	1.2	0	4.0	10.2	"	30.6	"	30.6
Rec.	1.0	3.0	0.5	4.5	1.0	4.0	13.5	3.5	47.2	d	47.2
	"	"	0	1.2	0	"	9.2	"	32.2	"	32.2
Data Proc.	1.0	3.0	0.5	4.5	1.0	4.0	13.5	8.0	108.0	d	10[illegible].0
	"	"	0	1.2	0	"	9.2	"	73.6	"	73.6
CCC											
Xmtr	1.0	4.0	0.5	4.5	1.0	4.0	14.5	3/3	14.5	d	14.5
	"	"	0	1.2	0	"	10.2	"	10.2	"	10.2
Rec.	1.0	3.0	0.5	4.5	1.0	4.0	13.5	3.5/3	15.8	d	15.8
	"	"	0	1.2	0	"	9.2	"	10.7	"	10.7
Data Proc	1.0	3.0	0.5	4.5	1.0	4.0	13.5	8/3	36.0	d	36.0
	"	"	0	1.2	0	"	9.2	"	24.5	"	24.5

$\Sigma u=0.0265,\ 0.0181$ $\Pi(1-u)=0.97376$

2

from squadron to site is significant, also, but is not susceptible to tradeoff at this level.

Either factor can be significantly reduced by adding a channel or a spare.

For the initial readiness computation, consideration of a single spare was conservative, since spares will be supplied at the assembly level, for 14 unique types. Referring to the interpolation method of Appendix III-9, it can be seen that detailed computation of the equivalent spares complement provided by one each of 14 types would be time consuming if done manually. A reasonable short-cut seems sufficient. This method consists of using the actual contributions for an arbitrary number of most significant assemblies in the radar, and averaging the contributions of the remaining radar assemblies. In addition, only the effect of two equivalent spares is considered.

The expression for unreadiness becomes

$$d=d_1-(d_1-d_2)\left[2\sum_{i}^{k}P_{ii})\left(1-\sum_{1}^{i}P_{ij}\right)+P_{ii}^{p}\,n!/(n-p)!\right]^{*} \qquad \text{IX-7}$$

where d=unreadiness

d_i=unreadiness numeric for (i) spares.

k= arbitrary number of significant P's.

P_{ii}=workload contribution + P_i/P_t

n=number of types averaged.

p= number of satisfied demands =2.

P_{ii}=averaged $P_i=\left(\sum_{k+1}^{k+n}P_{ii}\right)/n$

Analyzing the radar (see Table IX-10) with the asterisked demand rates selected as most significant,

k=4

n=2

P_{ii}=0.008

*For three equivalent spares

$$d=d_1-(d_1-d_2)\left[2\left(\sum_{1}^{k}P_{ii}\right)\left(1-\sum_{1}^{i}P_{ij}\right)+P^{2}_{ii}\,n!/(n-2)!\right]-(d_2-d_3)\left[6\left(\sum_{1}^{k}P_{ii}\right)\right.$$
$$\left.\left(1-\sum_{1}^{i}P_{ij}\right)\left(1-\sum_{1}^{j}P_{in}\right)+P_{ii}^{3}\,n!/(n-3)!\right] \qquad \text{IX-8}$$

TABLE IX-10

RADAR ASSEMBLY WORKLOAD CONTRIBUTIONS

Assembly	$\lambda x10^4$		P_{1i}	$1-\Sigma P_{1i}$
H. V. Power	0.1			
Amp. Exciter	14.0	*	0.087	0.913
RF Amp	80.0	*	0.495	0.418
Sig Proc.	27.0	*	0.168	0.250
Data Comm.	1.0			
Displays	39.0	*	0.242	0.008
Total	161.1		0.992	

$$P_{1e}=1-\sum_{1}^{k}P_{1i}=0.008$$

$$d = d_1 - (d_1 - d_2)\,[2(0.087 \times 0.913 + 0.495 \times 0.418$$

$$+ 0.168 \times 0.250 + 0.242 \times 0.008)$$

$$+ (2!/(0!)\,(0.008)^2\,]$$

$$= d_1 - (d_1 - d_2)\,(066 + 1.28 \times 10^{-4}$$

$$= d_1 - 0.66(d_1 - d_2$$

The contribution of the averaged (P_{ii}'s) is obviously insignificant.

Referring back to Table IX-4, for C=2

$$d_f = 0.023 - 0.66(0.023 - 0.005)$$

$$= 0.011$$

$$t_{wdf} = 0.011/00.016 \times 0.989$$

$$= 0.7$$

From Table IX-5

$$d_f = 0.082 - 0.66(0.082 - 0.022)$$

$$= 0.042$$

$$t_{wdf} = 0.042/0.0195 \times 0.958$$

$$= 2.2$$

Fromb Table IX-6

$$d_f = 0.077 - 0.66(0.077 - 0.036)$$

$$= 0.049$$

$$t_{wdf} = 0.049/0.0161 \times 0.951$$

$$= 3.2$$

Table IX-11 is constructed in the format of Tables IX-7, IX-8, and IX-9, to assess the effect of equivalent spares computation for the radar. Note that radar unreadiness is reduced

TABLE IX-11

RADAR UNREADINESS

	1	2	3	4	5	6	7	8	9	10	11
	t_1	t	t_{wdr}	t_{wdt}	t_{wdm}	T_s	$t_d=\sum_1^6 t_i$	λ	$d=\lambda t_d$ x10⁴	$f(d)$	$u\times10^4$
Site											
H. V. Pow.	0.2	0.5	0.7	2.2	3.2	4.0	10.8	10^{-5}	1.1	d	1.0
Amp Exc.	0.5	1.0	0.7	2.2	3.2	4.0	11.6	7×10^{-4}	81.2	d^2	0.7
R. F. Amp	0.5	0.5	0.7	2.2	3.2	4.0	11.1	10^{-3}	111	$28d^2$	34.5
Sig. Proc.	1.0	4.0	0.7	2.2	3.2	4.0	15.1	2.7×10^{-3}	408	d	408
Data Comm.	1.0	4.0	0.7	2.2	3.2	4.0	15.1	10^{-4}	15.1	d	15.1
Displ.	1.0	4.0	0.7	2.2	3.2	4.0	15.1	1.3×10^{-3}	196	d^2	3.8
CCC											
Displ.	1.0	4.0	0.7	2.2	3.2	4.0	15.1	$\frac{1.3}{3}\times10^{-3}$	65.4	d^2	0

TOTAL $\Sigma u=0.0463$ $\Pi(1-u)=0.95392$

2

from 0.062 to 0.046. Even this is conservative, since spares were only analyzed for contribution toward two effective spares.

2.3 Comparison of Alternatives

The feasibility of alternatives differing from the base system is analyzed simply by comparison of the differences. Once the base system is established, it becomes relatively easy to assess the effect of a change in the system.

2.3.1 Discard Feasibility

Since the operational readiness requirement can be met with repair at the field shop and since this location offers the least cost to repair, it is only necessary to compare the cost incurred at the field shop for assembly repair versus discard. The breakeven equation for discard is

$$\frac{C_p+C_{pp}+C_{te}\geq C_d}{F}$$

The inequality must hold for discard feasibility.

C_p = Cost of personnel

C_{pp} = Cost of piece parts

C_{te} = Cost of test equipment and support

F = Expected failures over ten years lifetime.

C_d = Mean subassembly cost.

The expected number of failures is

F = (aggregate failure rate)x(life)$=2\times10^{-1}\times8.77\times10^{4}=17{,}500$

The cost of piece parts per repair is assumed at $10.00.

One radar repair team and one test equipment repairman could be eliminated with subassembly discard, but the remaining radar team and those for Data Processing and Communications would remain necessary for assembly level repair and checkout. The number of personnel affected is

1/E-7 - \$8939/year*

4/E-5 - \$5172/year

2/E-3 - \$2724/year

including pipeline personnel.

The inequality becomes

$$C_p(2x\$2724x10 \text{ years} + 4x\$5172x10 \text{ years} + \$8939x10 \text{ years})$$

$$+C_{pp}(\$10 \times 17{,}500)+C_{te} \geq 17{,}500C_d$$

$$\$525{,}000 + C_{te} \geq 17{,}500C_d$$

Based upon Assembly Cost of

Assembly Cost	C_{te} Breakeven
\$50	\$350,000
\$100	\$1,225,000
\$200	\$2,975,000

The test equipment required for an eight-hour repair time at the field shop is estimated to cost less than \$200,000. Since the average subassembly contains approximately thirty piece parts at an approximate cost of ten dollars each, the highest economically feasible level of discard is the piece part.

Several costs are not included in the above analysis:

a. Line item entrance and maintenance - this is the same under either policy.

b. Transportation - routine non-cost means.

c. Manuals - anticipated to be the same under both alternatives.

d. Cost of maintenance vans \$25,000.

*Appendix VIII

e. Cost of utilities - this is estimated at $10,000, based on eight hours of operation per day.

The two critical error sources in the analysis above are failure rate and assembly cost. The tendency is to underestimate these parameters, thus any error is likely to cause underestimation of discard cost.

2.3.2 Fault Isolation Tradeoff

Fault isolation is accomplished to the greatest extent by operation personnel. Since manual isolation is capable of meeting the operational readiness requirement, and cost can only be increased by inclusion of other than general purpose equipment, manual isolation, by general purpose equipment is the selected alternative.

2.3.2 Assembly Repair Location

Assembly repair at the field shop is obviously less costly than at the squadron, for the following reasons.

1. Low-volume transportation is effectively free, being already provided for other purposes.

2. Centralization of repair requires only two repair channels and test equipement, vs. at least three (one at each squadron) for squadron repair.

3. A spare of each type would be necessary with squadron repair, or squadron repair workload elements would be $3T_s+t_r+t$, and downtime would have added factors $2T_s+t_r$, which would add in excess of 16 hours' downtime, and prevent the system from meeting operational readiness requirements.

2.3.4 Spares Location

If all spares are kept at sites, it might be possible to eliminate the squadron maintenance van, at an estimated cost of $25,000. Small vehicles would still be necessary for delivery of spares from squadron to sites, and for transportation of squadron maintenance personnel to repair at the sites.

No decrease in squadron personnel would be possible, and it would be necessary to add approximately 23 spare assemblies.

The breakdown equation is

$C_v \geq C_s$

The inequality is required for feasibility of spares at sites.

C_v = Cost of van = $25,000

C_s = Cost of additional spares.

The cost of the average assembly is estimated at $20,000.

The spares cost becomes $560,000, obviously more costly than squadron spares.

2.3.5 Field Shop Repair Equipment

The alternatives to be considered are two repair channels with general purpose equipment, and one repair channel with radar equipment mockups for isolation and checkout.

The cost inequality for selection of the mockups is

$C_p > C_{t.}$

C_p = Cost of personnel eliminated

$C_{t.}$ = Net cost of mockups

As for discard feasibility

C_p = $350,750 $> C_{t.}$

This seems a reasonable bound, and development of mockups is proposed.

3. CONCLUSION

The base system as analyzed is capable of meeting operational readiness requirements. The considerable cost of providing automatic fault isolation is found to be unnecessary to a system whose major unreadiness contribution is geography.

The radar workload at the field shop justifies investment in more efficient equipment there for fault isolation and checkout

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